MATERIALS DATA RELEASE MEMORANDA

Project 187-ab-1

(NASA-CR-132146) MATERIALS DATA RELEASE MEMORANDA (Aerojet-General Corp., Sacramento, Calif.) 226 p HC $13.50

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DATA RELEASE MEMORANDA

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FOREWORD

This document consists of Data Release Memoranda prepared in fulfillment of Project 187, Paragraphs a and b (1), (2) and (3), Phaseout Activities

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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SYMBOLS USED ON PAGES 2 - 5

$\bar{X}$ = GROUP AVERAGES

n = SAMPLE SIZE ASSOCIATED WITH $\bar{X}$

f = DEGREES OF FREEDOM FOR POOLED WITHIN-GROUP STANDARD DEVIATION

k = 99/95 LOWER TOLERANCE LIMIT FACTOR FOR n AND f

s = POOLED WITHIN-GROUP STANDARD DEVIATION

PREPARED BY: M J Davidson

REVIEWED BY: M Shew

CLASSIFICATION:

UNCLASSIFIED

PER M J Davidson

DATE 3/2/72

MATERIAL INCONEL 718 FORM FORGING CONDITION SOLUTION ANNEALED AND DOUBLE AGED

SPECIFICATIONS AGC 90093-2

PROPERTY TENSILE ULTIMATE STRENGTH, KSI, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)		$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED 2.9×10^{17}	**	244.5	1.55	8	13	3.67	238.8	C	(1)
4.2×10^{18}		248.6	1.55	4	13	3.85	242.6	C	(1)
4.2×10^{18} + 540°R ANNEAL *		241.6	1.55	4	13	3.85	235.6	C	(1)

* 100 MINUTES

** NO SIGNIFICANT DIFFERENCE BETWEEN GROUPS; THEREFORE DATA POOLED.

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

MATERIAL INCONEL 718 FORM FORGING CONDITION SOLUTION ANNEALED AND DOUBLE AGED

SPECIFICATIONS AGC 90093-2

PROPERTY TENSILE YIELD STRENGTH, KSI, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)	$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED	197.1	1.68	4	12	3.91	190.5	C	(1)
2.9×10^{17}	206.4	1.68	4	12	3.91	199.8	C	(1)
4.2×10^{18}	233.6	1.68	4	12	3.91	227.0	C	(1)
4.2×10^{18} + 540°R ANNEAL *	214.7	1.68	4	12	3.91	208.1	C	(1)

* 100 MINUTES

NOTE: FOR MATERIAL EVALUATION ONLY; DO NOT USE FOR DESIGN.

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MATERIAL INCONEL 718 FORM FORGING CONDITION SOLUTION ANNEALED AND DOUBLE AGED

SPECIFICATIONS AGC 90093-2

PROPERTY ELONGATION, % @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)	$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED	22.9	2.65	4	12	3.91	12.5	C	(1)
2.9×10^{17}	19.4	2.65	4	12	3.91	9.0	C	(1)
4.2×10^{18}	12.3	2.65	4	12	3.91	1.9	C	(1)
4.2×10^{18} + 540°R ANNEAL *	19.9	2.65	4	12	3.91	9.5	C	(1)

* 100 MINUTES

NOTE: FOR MATERIAL EVALUATION ONLY; DO NOT USE FOR DESIGN.

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MATERIAL INCONEL 718 FORM FORGING CONDITION SOLUTION ANNEALED AND DOUBLE AGED

SPECIFICATIONS AGC 90093-2

PROPERTY FRACTURE TOUGHNESS, K_Q, KSI - $IN^{1/2}$, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)	$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED	145.6	7.24	5	13	3.78	118.2	C	(1)
3.0 X 10^{17}	135.6	7.24	4	13	3.85	107.7	C	(1)
3.9 X 10^{18}	122.9	7.24	4	13	3.85	95.0	C	(1)
3.9 X 10^{18} + 540°R ANNEAL *	135.5	7.24	4	13	3.85	107.6	C	(1)

* 100 MINUTES

NOTE: FOR MATERIAL EVALUATION ONLY; DO NOT USE FOR DESIGN

I. TEST DESCRIPTION (REFERENCE (1))

Round button-head tensile specimens per AGC P/N 1134298 and fracture toughness specimens per AGC P/N 1137229 were prepared from an Inconel 718 forging. The forging was made by Viking from Heat No. 86582. It was solution annealed at 1950°F, held one hour and rapid air cooled per AGC Specification 90093 and 46604B. Heat treatment was performed by Viking. Following rough machining of specimens, the blanks were double aged at 1350 and 1200°F per AGC 46604.

The specimens were irradiated at Convair Aerospace Division/ Fort Worth as part of test GTR-20C. Two different fluence levels were attained. In addition, some specimens irradiated to the highest fluence were annealed for 100 minutes at 540°R prior to testing. The irradiated specimens and a control group were tested at 140°R. The results of the tests are shown in the following tables in which each entry is the average of 4 or 5 specimens.

TENSILE TESTS

Fluence n/cm^2, E > 1 MeV	Post-Irradiation Anneal, 540°R (Minutes)	No. of Specimens	Ultimate Strength (ksi)	Yield Strength (ksi)	Elongation %
Unirradiated	0	4	244.4	197.1	22.9
2.9×10^{17}	0	4	244.6	206.4	19.4
4.2×10^{18}	0	4	248.6	233.6	12.4
4.2×10^{18}	100	4	241.6	214.7	19.9

FRACTURE TOUGHNESS TESTS

Fluence n/cm^2, E > 1 MeV	Post-Irradiation Anneal, 540°R (Minutes)	No. of Specimens	Fracture Toughness, K_Q (ksi - $in^{1/2}$)
Unirradiated	0	5	145.6
3.0×10^{17}	0	4	135.6
3.9×10^{18}	0	4	122.9
3.9×10^{18}	100	4	135.5

II. DATA ANALYSIS

Ultimate Strength

There was no significant difference between the ultimate strength of unirradiated specimens and those irradiated to 2.9×10^{17} n/cm^2. Therefore, these data were pooled for calculation of mean and 99/95 lower limit. Specimens irradiated to 4.2×10^{18} n/cm^2 showed an increase in ultimate strength which was removed by annealing at 540°R. These data are shown separately. The variances were homogeneous and therefore pooled for calculation of a pooled standard deviation.

Yield Strength

The yield strength of the specimens increased with each increasing fluence level. The effect of radiation was partially removed by annealing at 540°R. Therefore, each group of data is shown individually. The variances were homogeneous so all data were pooled for calculation of a standard deviation.

Elongation

The elongation of the specimens decreased with each increasing fluence level. The effect of radiation was partially removed by annealing at 540°R. Accordingly, each group of data is shown individually. The data were pooled for calculation of a standard deviation.

Fracture Toughness

The fracture toughness of the specimens decreased with each increasing fluence. The fracture toughness was partially restored by annealing at 540°R. Each group of data is individually tabulated. The data from all groups were pooled for calculation of a standard deviation.

III. REFERENCES

(1) General Dynamics, Convair Aerospace Division FZK-381, NERVA Irradiation Program, GTR-20C, Combined Effects of Reactor Radiation and Cryogenic Temperature on NERVA Structural Materials, May 1971.

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

CONTENTS

PREPARED BY: M J Davidson

REVIEWED BY: M Slev

CLASSIFICATION:

UNCLASSIFED

PER M J Davidson

DATE 21 March 1972

MATERIAL INCONEL 718 FORM FORGING CONDITION SOLUTION ANNEALED AND DOUBLE AGED

SPECIFICATION AGC 90093-2

PROPERTY ULTIMATE NOTCHED TENSILE STRENGTH KSI @ 80°F

FLUENCE, N/CM^2 (E > 1.0 MeV)	GASEOUS ENVIRONMENT	NO. OF OBSERVATIONS	MEAN VALUE	ESTIMATED STANDARD DEVIATION	ESTIMATED * DESIGN ALLOWABLE	DATA CATEGORY	REFERENCE
UNIRRADIATED	HYDROGEN	3	252.3	4.6	239.0	C	(1)
UNIRRADIATED	HELIUM	1	267.5	4.6	253.7	C	(1)
1.5×10^{20}	HYDROGEN	2	292.5	4.6	278.7	C	(2)
1.5×10^{20}	HELIUM	2	292.5	4.6	278.7	C	(2)

* CONSERVATIVE ENGINEERING ESTIMATE, NOT 99/95 LIMIT.

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

I. TEST DESCRIPTION

Button-head notched tensile specimens per AGC P/N 1137556 were prepared from an Inconel 718 forging. The forging was made by Viking from Heat No. 86582. It was solution annealed by Viking at 1950°F and rapid air cooled. Following rough machining, the blanks were double aged at 1350 and 1200°F.

The specimens were irradiated in water at Plumbrook Reactor Facility and post irradiation tested in 1500 psig H_2 or He by Convair Aerospace Division/Fort Worth. In addition, unirradiated specimens were tested in 1200 psig H_2 or He at Aerojet Liquid Rocket Company. The results are shown in the following table where each entry is the average of the indicated number of specimens.

Fluence n/cm^2, E $>$1.0 MeV	Gaseous Environment	No. of Specimens	Ultimate Strength, ksi
Unirradiated	H_2	3	252.8
Unirradiated	He	1	267.5
1.5×10^{20}	H_2	2	292.5
1.5×10^{20}	He	2	292.5

II. DATA ANALYSIS

The variances of the data from each group were homogeneous and therefore pooled for estimating the standard deviation. A conservative engineering estimate of the design allowable was made by subtracting 3 standard deviations from the mean. The unirradiated specimens showed slight embrittlement due to hydrogen. The irradiation specimens exhibited an increase in ultimate tensile strength and showed no embrittlement due to hydrogen. Reference (2) recommends additional testing to verify the absence of hydrogen embrittlement in irradiated specimens.

III. REFERENCES

(1) "NERVA Tensile Test Report" Research Physics Laboratory, ALRC, 26 July 1971.

(2) General Dynamics, Convair Aerospace Division FZK-379, Hydrogen Embrittlement of Irradiated Alloys, May 1971.

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

CONTENTS

PREPARED BY: M Shev

REVIEWED BY: [illegible signature]

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 3/24/72

MATERIAL SS 347 FORM ALL CONDITION ALL

SPECIFICATIONS AMS 5646E

PROPERTY DYNAMIC MODULUS, KSI (X 10^6)

TEMPERATURE °F	NO. OF OPERATIONS	MEAN VALUE $\bar{X}$	STANDARD DEVIATION s	DEGREES OF FREEDOM f	TOLERANCE LIMIT FACTOR k	DESIGN ALLOWABLES LOWER	DESIGN ALLOWABLES UPPER	DATA CATEGORY	SOURCE REFERENCE
-320	5	31.57	0.51	10	4.45	29.3	33.8	C	1
RT	4	28.55	0.51	10	4.53	26.2	30.9	C	1
600	4	26.52	0.51	10	4.53	24.2	28.8	C	1

MATERIAL SS 347 FORM ALL CONDITION ALL

SPECIFICATIONS AMS 5646E

PROPERTY POISSON'S RATIO

TEMPERATURE °F	OPERATIONS	MEAN VALUE $\bar{X}$	STANDARD DEVIATION s	DEGREES OF FREEDOM f	TOLERANCE LIMIT FACTOR k	DESIGN ALLOWABLES LOWER	DESIGN ALLOWABLES UPPER	DATA CATEGORY	SOURCE REFERENCE
-320	5	.2625	.0085	10	4.45	.225	.300	C	1
RT	4	.2918	.0085	10	4.53	.253	.330	C	1
600	4	.2928	.0085	10	4.53	.254	.331	C	1

I. TEST DESCRIPTION

Dynamic Modulus and Poisson's ratio of SS 347 at -320°F, RT, and 600°F were measured by WANL per ANSC P.O. N-01728. The material submitted for testing was 4" diameter bar stock from Universal Cyclops Heat No. G-5875, heat treated to the simulated furnace-brazed condition.

A single test specimen, per ANSC P/N 1138310, was fabricated from the bar stock and used for all the determinations. An ultrasonic technique described in Reference (1), was used. Five determinations were made at room temperature and four each at the other two temperatures. The results are reported in Reference (2). Averages for each temperature are shown on pages 2 and 3. The results are considered to apply to all forms and conditions of SS 347.

II. DATA ANALYSIS

Normally, design values for these physical properties would be reported as nominal $\pm$ 5%. (Reference (3)). However, since the replicate determinations provide a measure of experimental error variability, the design values were calculated as true 99/95 limits. All variability is attributed to test error rather than to the material.

The within-temperature variances were found to be homogeneous by means of the Bartlett-Box test and accordingly were pooled into a single variance estimate, s^2, based on 10 degrees of freedom. Two-sided tolerance limit factors, k, were determined from Reference (4). Finally, 99/95 limits were calculated as $\bar{X} \pm ks$.

III. REFERENCES

1. WANL Test Plan 38-10, Project 485G, dated 5 August 1970.

2. Letter from R. F. Dickson (WANL) to J. L. Dooling (ANSC) dated 22 October 1971, Subject: "Project 485, Test Plan M-38, Line 10, Requisition No. N-01728: Dynamic Modulus Tests".

3. Letter L. C. Corrington (SNSO-C) to W. O. Wetmore (ANSC) dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data".

4. A. Weissberg and G. H. Beatty, "Tables of Tolerance - Limit Factors for Normal Distributions", Technometrics, Vol. 2, No. 4 page 483-500 (1960).

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

CONTENTS

PREPARED BY: M Shev

REVIEWED BY: C. Nessan

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 4/7/72

MATERIAL SS 347 FORM BAR CONDITION SIMULATED BRAZE

SPECIFICATIONS QQS-763

PROPERTY LOW-CYCLE FATIGUE LIFE (HYDROGEN GAS ENVIRONMENT)

TEMP. °F	TOTAL STRAIN %	LOG OF CYCLES = MEAN	s_e	n_e	f	k	99/95 LOWER LIMIT	NUMBER OF CYCLES 50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
1000	5.0	2.132	.0520	3	18	3.76	1.896	125	79	A	(1)
	4.5	2.203		4		3.65	1.973	160	94		
	4.0	2.288		5		3.58	2.063	194	116		
	3.5	2.392		7		3.49	2.172	247	149		
	3.0	2.521		8		3.46	2.303	332	201		
	2.5	2.687		8		3.46	2.469	486	294		
	2.0	2.909		6		3.53	2.687	811	486		
	1.5	3.266		3		3.76	2.990	1684	976		
1400	5.0	2.079	.0880	3	22	3.67	1.756	120	57	A	(1)
	4.5	2.145		4		3.56	1.832	140	68		
	4.0	2.218		5		3.48	1.912	165	82		
	3.5	2.301		7		3.39	2.003	200	101		
	3.0	2.397		8		3.34	2.103	250	127		
	2.5	2.511		8		3.34	2.217	324	165		
	2.0	2.650		6		3.43	2.348	447	223		
	1.5	2.829		3		3.67	2.506	675	321		
1600	5.0	2.320	.1565	3	23	3.65	1.749	209	56	A	(1)
	4.5	2.407		4		3.54	1.853	255	71		
	4.0	2.505		6		3.41	1.971	320	93		
	3.5	2.607		7		3.37	2.079	412	120		
	3.0	2.710		9		3.32	2.190	553	155		
	2.5	2.832		9		3.32	2.312	783	205		
	2.0	2.981		7		3.37	2.454	1198	284		
	1.5	3.174		4		3.54	2.620	2073	417		

s_e = STANDARD ERROR OF ESTIMATE
n_e = EFFECTIVE SAMPLE SIZE
f = DEGREES OF FREEDOM FOR s_e
k = 99/95 LOWER TOLERANCE LIMIT FACTOR FOR n_e AND f

I. TEST DESCRIPTION

This DRM is based upon work performed by Battelle Memorial Institute per ANSC P. O. No. N900105 and reported in Reference (1). The material used was SS 347 3/4" diameter bar stock that had been heat-treated to simulate the brazing operations used in NERVA nozzle fabrication. The bar stock was from three different heats of material as follows:

X-11585 (Crucible Steel), designated "Lot A"

G-5617 (Universal Cyclops), designated "Lot B"

G-4943 (Universal Cyclops), designated "Lot C"

Low cycle fatigue specimens were prepared from all three heats. These were subjected to constant amplitude strain-controlled compressive strain cycling at a constant strain rate of 10^{-3} sec^{-1}. The tests were conducted in a purified hydrogen gas environment at temperatures of 1000, 1400 and 1600°F. The total strain ranges used were 1.5, 3.0, and 5.0 percent, according to the following test matrix which shows the number of specimens at each condition.

		Temp. °F		
Heat	% Total Strain (Approx.)	1000	1400	1600
X-11585	1.5	3	4	3
	3.0	3	3	3
	5.0	3	3	3
G-5617	1.5	3	3	4
	3.0	3	3	3
	5.0	3	3	3
G-4943	1.5	3	3	4
	3.0	3	3	3
	5.0	3	3	3

Cycles to failure and total measured strain range for each of the specimens are shown in the following table.

	Lot A Heat X-11585		Lot B Heat G-5617		Lot C Heat G-4943	
	Percent Total Strain	Cycles To Failure	Percent Total Strain	Cycles To Failure	Percent Total Strain	Cycles To Failure
1000°F	4.92	132	4.94	124	4.93	155
	4.97	170	4.94	142	4.93	164
	4.89	172	4.92	150	4.92	174
	2.92	300	2.91	327	2.95	336
	2.92	401	2.92	339	2.91	372
	2.96	403	2.89	405	2.92	397
	1.49	1856	1.48	1590	1.50	1369
	1.48	1975	1.38	1877	1.49	1952
	1.46	2251	1.39	2536	1.47	2443
1400°F	4.89	113	4.88	102	4.92	111
	4.88	119	4.88	150	4.87	135
	4.89	168	4.87	162	4.85	191
	2.96	214	2.94	162	2.95	238
	2.96	280	2.94	258	2.95	299
	2.94	286	2.95	260	2.95	368
	1.49	677	1.49	648	1.46	796
	1.49	691	1.49	739	1.49	822
	1.45	700	1.50	790	1.50	950
	1.49	820				
1600°F	4.97	356	4.96	359	5.12	139
	4.97	241	5.30	294	4.95	482
	4.93	178	4.96	151	5.32	190
	2.98	754	2.97	479	2.94	553
	3.20	437	2.94	517	2.94	479
	2.96	446	3.00	232	2.94	516
	1.28	2111	1.48	2245	1.70	767
	1.44	2000	1.50	2124	1.48	1889
	1.47	1821	1.44	2545	1.50	1522
			1.48	2850	1.45	1913

II. DATA ANALYSIS

Statistical analysis of the data is reported in Reference (2). The method of regression analysis was used, with the aid of the G.E. Mark I computer program MULFT$. The three temperatures were handled separately. Within each temperature, a separate regression equation was computed for each of the three heats. In these equations, the independent variable was log of percent strain and the dependent variable was log of cycle life. At 1000°F, a quadratic equation in these variables exhibited the best fit, while at the other two temperatures, a linear relationship (of the logarithms) was adequate. Variation among the three lots was minor.

The further analysis in Reference (2) was based on the statistical guidelines in effect at the time. Heat-to-heat variation was considered to be a random variable. The regression equations for the individual lots were combined, and the variance components (within and among lots) were computed, added together, and used to calculate design allowables at various strain levels.

The guidelines in effect at present permit the use of this method only when there are eight or more lots. (Reference (3)). Therefore, the balance of the data analysis for this DRM deviated from that of Reference (2). The method of the lowest lot mean was used. For each temperature, that lot exhibiting the lowest expected fatigue life within the strain range of interest (1.5 to 5%) was selected. At 1000° and 1400°F, Heat G-5617 was the lowest at all strain levels. At 1600°F, the regression lines for heats G-5617 and G-4943 intersected; G-4943 was lowest between 1.5 and 3.5% strain and G-5617 was lowest between 4 and 5% strain.

The regression equations for these lowest lots were:*

1000°F (Lot B)	$\log N_f = 3.733 - 3.0817 \log x + 1.135 (\log x)^2$
1400°F (Lot B)	$\log N_f = 3.0811 - 1.4340 \log x$
1600°F (Lot B)	$\log N_f = 3.6516 - 1.9062 \log x$
1600°F (Lot C)	$\log N_f = 3.4450 - 1.5426 \log x$

where N_f = number of cycles to failure

x = total strain, %

* NOTE: These equations were taken from Reference (2), but were converted from $\log_e$ to $\log_{10}$ to conform with other DRM's.

For each temperature, the within-lot standard errors f estimate were pooled over the three lots. For each strain level, the expected number of cycles (in log form) was calculated from the regression equations and the 99/95 lower limit calculated as

$\bar{X}_L - ks_e$, where $\bar{X}_L$ is the expected value for the strain level (based on the lowest lot), s_e is the pooled standard error of estimate and k is the 99/95 one-sided tolerance factor based on an effective sample size (n_e)

for the single lot, and degrees of freedom (f) for the pooled standard deviation. Finally, both the expected values and the lower limits were converted back to anti-log form , i.e., number of cycles to failure.

The data are classified as "A" on the basis of meeting all the revised requirements of TD 69-28 and 69-37.

III. REFERENCES

(1) C. E. Jaske and T. L. Porfilio "Final Report on Low-Cycle Fatigue of Type 347 Stainless Steel and Hastelloy X in Hydrogen Gas Environment", Battelle Memorial Institute, Columbus, Ohio, dated 20 December 1971.

(2) Memorandum N8200:M3053, from A. J. Mihanovich to R. G. Ackerman, dated 18 October 1971, Subject: Statistical Analysis of 347 Stainless Steel and Hastelloy X Fatigue Test Results.

(3) Letter, M&S:JJL, L. C. Corrington to W. O. Wetmore dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data, Enclosure (1) Paragraph 5."

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

CONTENTS

PREPARED BY: M Sher

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Sher

DATE 4/7/72

27

MATERIAL SS 347 FORM PLATE (PARENT METAL AND WELD) CONDITION ANNEALED

SPECIFICATIONS MIL-S6721B, QQ-S-766

PROPERTY LOW CYCLE FATIGUE LIFE @ 1000°F

STRAIN RANGE %	LOG OF CYCLES TO FAILURE MEAN	s	n	f	k	99/95 LOWER LIMIT	CYCLES TO FAILURE 50 % POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
A. PARENT METAL (INCLUDING HEAT AFFECTED ZONE)										
1.5	3.162	.120	8	8	4.16	2.663	1452	460	C	1, 2
1.0	3.684	.120	4	8	4.32	3.166	4831	1464	C	1
B. WELDED MATERIAL										
1.5	2.786	.120	2	8	4.59	2.235	611	172	C	1
1.0	3.200	.120	2	8	4.59	2.649	1585	446	C	1

s = POOLED WITHIN-GROUP STANDARD DEVIATION

n = NUMBER OF OBSERVATIONS

f = NUMBER OF DEGREES OF FREEDOM FOR s

k = 99/95 TOLERANCE LIMIT FACTOR FOR n AND f

I. TEST DESCRIPTION

This DRM is based on low cycle fatigue testing of SS 347 (parent metal and welds) for the NASS Duct Program performed by Mar-Test, Inc. under ANSC Purchase Order No. N-01444, and reported in Reference 1.

The material consisted of two pieces of 3/4" plate from Alleghany Ludlum Heat Number 39109. One plate was parent metal and the other contained a weld down its middle.

Low cycle fatigue specimens were fabricated from the plates so that four were of parent metal, four had the midpoint of the weld at the minimum diameter of the gage section and four had the minimum diameter of the gage section offset 0.6 inch from the weld centerline in order to evaluate the heat-affected zone.

The twelve specimens were subjected to compression-tension cycling (R=-1) at an axial strain rate of 10^{-3} sec^{-1}, and at total axial strain ranges of 1.0 and 1.5 percent. Two specimens of each type were tested at each strain range. Tests were performed in air at 1000°F.

A supplementary test program (References 2 and 3) was conducted to compare compression-tension (R=-1) cycling with compression-compression cycling (R=-∞). Four specimens were used, all parent metal, all at strain ratios of 1.5% and two at each R-ratio.

The following results were obtained:

Specimen Type	R-Ratio	Total Strain Range, %	Nf Cycles to Failure
Parent Metal	-1	1.5	1539
		1.5	1828
		1.0	5364
		1.0	5193
Weld	-1	1.5	742
		1.5	504
		1.0	2554
		1.0	984
Heat-Affected Zone	-1	1.5	13.65
		1.5	1376
		1.0	5168
		1.0	3776
Parent Metal (Reference 2)	$-\infty$	1.5	1367
	$-\infty$	1.5	1510
	-1	1.5	1447
	-1	1.5	1261

II. DATA ANALYSIS

Statistical analysis employed the log of cycles to failure. There was no significant difference between the compression-compression and the compression-tension tests. Accordingly, the four data points in the supplementary program were consolidated and pooled with the two observations on parent metal at 1.5% from the main test program. Analysis of variance also indicated no significant difference between parent material and heat-affected material. Therefore these groups were combined at the two strain ranges.

Within-group variances were found to be homogeneous and were pooled. Tolerance limit factors, k, were found in the usual manner and the lower 99/95 limits for log cycle life were calculated as $\bar{X}$-ks for each group and strain level. Finally, the means and design allowables were converted to anti-log form (number of cycles).

It is of interest that the expected cycle life for parent metal at 1.5% strain (1464 cycles to failure) agrees closely with the results obtained by Battelle at the same strain level and reported in Reference 4. (1684 cycles).

III. <u>REFERENCES</u>

1. Mar-Test, Inc. Report, dated July 1971, "An Evaluation of the Low-Cycle Fatigue Resistance of 347 Stainless Steel at 1000°F".

2. Mar-Test, Inc. Report, dated December 1971, "An Evaluation of the Low-Cycle Fatigue Resistance of 347 Stainless Steel at 1000°F Using Compression-Compression Loading".

3. Materials Memorandum N8130:0121, from H. W. Spaletta to T. A. Redfield, dated 25 August 1971, Subject: Status Report for Low Cycle Fatigue Tests being Conducted by Mar-Test, Inc.

4. DRM 02.13, dated 5 April 1972.

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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EXPLANATION OF SYMBOLS ON PAGES 2 AND 3:

s_e = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)
n_e = EFFECTIVE SAMPLE SIZE
f = DEGREES OF FREEDOM FOR s_e
k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

PREPARED BY: M Shew
REVIEWED BY: P. Nessa

CLASSIFICATION:
UNCLASSIFIED
PER M Shew
DATE 4/24/72

MATERIAL SS 347 FORM SHEET CONDITION TRIPLE-BRAZED

SPECIFICATIONS QQ-S-766C, AGC 90006D

PROPERTY TIME FOR 1% TOTAL CREEP, HOURS

TEMP °F	STRESS KSI	LOG OF HOURS MEAN	s_e	n_e	f	k	99/95 LIMIT	50% POINT	DESIGN ALLOWABLE	CONTROLLING* LOT	DATA CATEGORY	SOURCE REFERENCE
1200	24	-0.772	0.183	3	41	3.48	-1.409	0.17	0.04	B	A	1
	22	0.368	0.183	8	41	3.16	-0.210	2.34	0.62	C		
	20	1.104	0.183	21	41	2.99	0.557	12.71	3.6	C		
	18	1.734	0.183	15	41	3.03	1.180	54.21	15.1	C		
1400	10	0.300	0.174	9	57	3.06	-0.232	2.00	0.59	A	A	
	8	.679	0.174	17	57	2.94	0.168	4.77	1.47	A		
	6	1.050	0.174	10	57	3.04	0.521	11.23	3.32	A		
	4	1.352	0.174	2	57	3.63	0.721	22.50	5.26	C		
1600	4	-0.348	0.143	6	51	3.19	-0.804	0.45	0.16	A	A	
	3	-0.0427	0.143	8	51	3.11	-0.487	0.91	0.33	A		
	2	0.388	0.143	14	51	2.99	-0.040	2.44	0.91	A		
	1	1.124	0.143	19	51	2.94	0.704	13.32	5.05	A		

* LOT HAVING LOWEST EXPECTED TIME FOR 1% CREEP AT SPECIFIED TEMPERATURE AND STRESS.

MATERIAL SS 347 FORM SHEET CONDITION TRIPLE-BRAZED

SPECIFICATIONS QQ-S-766C, AGC 90006D

PROPERTY TIME FOR 3% TOTAL CREEP, HOURS

TEMP °F	STRESS KSI	LOG OF HOURS MEAN	s_e	n_e	f	k	99/95 LIMIT	50% POINT	DESIGN ALLOWABLE	CONTROLLING* LOT	DATA CATEGORY	SOURCE REFERENCE
1200	24	1.292	.0719	4	38	3.38	1.049	19.57	11.1	C	A	1
	22	1.762	.0719	8	38	3.17	1.534	57.80	34.2	C	A	
	20	1.943	.0719	19	38	3.02	1.726	87.65	53.2	C	A	
	18	2.143	.0719	4	38	3.38	1.900	138.90	79.4	A	A	
1400	10	0.788	.146	9	49	3.08	0.338	6.14	2.2	A	A	
	8	1.134	.146	17	49	2.97	0.700	13.60	5.0	A	A	
	6	1.579	.146	10	49	3.06	1.132	37.93	13.6	A	A	
	4	2.207	.146	2	49	3.65	1.674	160.93	47.2	A	B	
1600	4	0.163	.132	14	40	3.05	-0.240	1.45	0.58	A	A	
	3	0.495	.132	14	40	3.06	0.092	3.12	1.2	A	A	
	2	0.934	.132	8	40	3.16	0.517	8.59	3.3	A	A	
	1	1.607	.132	5	40	3.29	1.173	40.42	14.9	A	A	

* LOT HAVING LOWEST EXPECTED TIME FOR 3% CREEP AT SPECIFIED TEMPERATURE AND STRESS.

1. TEST DESCRIPTION

This DRM is based upon work performed by General Electric Nuclear Systems Programs, Space Division, Cincinnati, Ohio, under ANSC P.O. N-900104 and reported in Reference (1).

Three lots of SS 347 sheet, .016" thick were used in the test program. The lots were identified as A, B and C and represented material produced by Washington, Republic, and Jones & Laughlin Steel Companies, respectively. All three lots were subjected to a final heat treatment (simulated furnace braze cycle) by Pyromet.

Creep specimens were fabricated from the sheet stock, 80 specimens from each lot. These were further sub-divided into 3 groups for creep testing at 1200°, 1400° and 1600°F. All tests took place in hydrogen atmosphere.

Various loads were applied to the different specimens and held until the total creep exceeded 3%. Creep vs time curves were plotted for each specimen, and the time in hours for 1/2%, 1% and 3% was interpolated from these plots and recorded.

The test matrix, showing the number of usable test results from each lot, and at each temperature and stress level is given in the table below. The total number of tests reported by G.E. was 194 of which 6 were stated to have yielded no data because of extensometer malfunctions, leaving 188. Of these, 10 never reached 1% creep and 3 others were discarded as statistical outliers, leaving a total of 175 observations at 1% creep, and a smaller number, as shown, at 3% creep.

TEST TEMP.	1200°F			1400°F			1600°F			
LOT / ESS, KSI	A	B	C	A	B	C	A	B	C	
17	3*	2	3							
18	-	-	5***							
19	1*	3	8*							
20	3	3	3							
22	3	3	3							
24	3	2#	2							
3.5				1	-	(10)				
5				2	2	2				
7				5	6	7				
8.5				5	4	5				
10				5	5	5				
13				-	1	-				
15				-	1	-				
0.5							4***	1*	3***	
0.7							4	2**		
0.8							2	-	1	
1.0							3	4	5	
1.3							-	-	2	
1.5							2	2	3*	
2.0							-	3	-	
3.0							3	3	3	GRAND
4.5							3	3	3	TOTAL
tals at creep	13	13	24	18	19	29	21	18	20	175
tals at creep	11	14	20	18	19	19	18	15	16	150

NOTES:
1. Each * indicates one specimen which failed to reach 3% creep.
2. # indicates an observation that was discarded as an outlier at 1% creep, but yielded a valid result at 3% creep.
3. ( ) indicates that the 10 specimens were tested to 1% creep only, with no results at 3%.

2. DATA ANALYSIS

The method of regression analysis was used, with the aid of the G.E. computer program MULFIT. The two dependent variables were time to 1% creep and time to 3% creep. Because, as shown above, all specimens did not reach 3%, the two creep times were handled as separate analyses. Although time to 0.5% creep is also reported in Reference (1), the data were not analyzed.

The three test temperatures necessitated three completely different ranges of stress; therefore each temperature was handled in a separate analysis.

Substantial differences in creep among the three lots were observed. In Reference (1), these were related to difference in grain size as follows:

> "The creep results of the three lots appeared to be consistent with the grain size observations; i.e., the larger grain material had a greater resistance to creep than fine-grain material under the same test conditions, particularly at the higher temperatures".

In keeping with the latest guidelines for data analysis (Reference(2), separate regression equations were obtained for each lot, and the reported means and design allowables are based on that lot having the shortest creep time for the specified temperature and stress level. The standard errors of estimate used were pooled over all three lots, the pooling being justified by means of the Bartlett-Box test for homogeneity.

Two regression models were considered: (1) a linear relationship between the log of time and the log of stress, i.e., a straight line on log-log paper and (2) a quadratic relationship between the same variables in logarithmic form, i.e., a parabola on log-log paper. The quadratic model was used whenever it exhibited a substantially better fit (a lower standard error of estimate) than the linear model; otherwise the linear model was used.

The results of the regression analysis were as follows:

TIME TO 1% CREEP

TEST TEMP °F	LOT	n	REGRESSION EQUATION*	STD.** ERROR OF ESTIMATE	INDEX OF DETER-MINATION
1200	A	13	$\log y = -35.565 + 69.008 \log x -31.204 (\log x)^2$	.146	.955
	B	13	$\log y = -262.74 + 424.763 \log x -170.235 (\log x)^2$	.191	.966
	C	24	$\log y = -56.161 + 103.903 \log x -46.031 (\log x)^2$	.194	.925
			POOLED	.183	
1400	A	18	$\log y = 0.423 + 4.064 \log x -4.187 (\log x)^2$	.204	.730
	B	19	$\log y = 1.548 + 4.843 \log x -5.535 (\log x)^2$	.168	.937
	C	29	$\log y = -0.889 + 10.197 \log x -9.033 (\log x)^2$	.157	.943
			POOLED	.174	
1600	A	21	$\log y = 1.125 -2.4466 \log x$	.153	.966
	B	18	$\log y = 1.745 -1.883 \log x -1.217 (\log x)^2$	.130	.967
	C	20	$\log y = 1.425 -2.076 \log x -1.119 (\log x)^2$	.141	.968
			POOLED	.143	

TIME TO 3% CREEP

TEST TEMP °F	LOT	n	REGRESSION EQUATION*	STD.** ERROR OF ESTIMATE	INDEX OF DETER-MINATION
1200	A	11	$\log y = -69.739 + 117.48 \log x - 47.831 (\log x)^2$	.0994	.944
	B	14	$\log y = 7.674 - 4.136 \log x$	.0578	.925
	C	20	$\log y = 7.628 - 4.370 \log x$	.0656	.896
			POOLED	.0719	
1400	A	18	$\log y = 4.353 - 3.565 \log x$	.101	.949
	B	19	$\log y = 5.194 - 3.749 \log x$	.170	.873
	C	19	$\log y = -0.420 + 8.994 \log x - 7.604 (\log x)^2$	.155	.858
			POOLED	.146	
1600	A	18	$\log y = 1.6066 - 2.072 \log x - .543 (\log x)^2$	.0885	.986
	B	15	$\log y = 2.239 - 1.180 \log x - 2.282 (\log x)^2$	.164	.936
	C	16	$\log y = 1.994 - 1.868 \log x - 1.541 (\log x)^2$	.174	.940
			POOLED	.132	

* x = stress level, ksi
y = mean time to stated % creep, hours

** in logarithmic units

The standard errors of estimate were pooled over the three lots at a given temperature. The expected values of log y were computed for various stress levels in order to determine the lot with the shortest creep time. The identity of these lots are shown on Pages 2 and 3 as "Controlling Lot" and in the great majority of cases was Lot A. The mean times for the three lots are shown graphically in Figures 1 and 2.

Lower 99/95 limits for log of creep time were calculated as log y_L - ks where y_L is the creep time of the lowest lot, s is the pooled standard error of estimate and k is the tolerance limit factor based on f (the degrees of freedom for s_e) and n_e the expected sample size for the particular stress level. Finally, both the mean values and the lower limits were converted to the anti-log form (hours). The lower limits or design allowables are plotted in Figures 1 and 2.

The data are categorized as "A", having met the requirements of TD-69-37, revised version.

3. REFERENCES

(1) GESP-723 "Final Report, Creep of 347 Stainless Steel in Hydrogen", General Electric Company, Nuclear Systems Programs, Space Division, dated 15 March 1972.

(2) Letter, M&S:JJL, L. C. Corrington to W. O. Wetmore dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data, Enclosure (1), Paragraph 5."

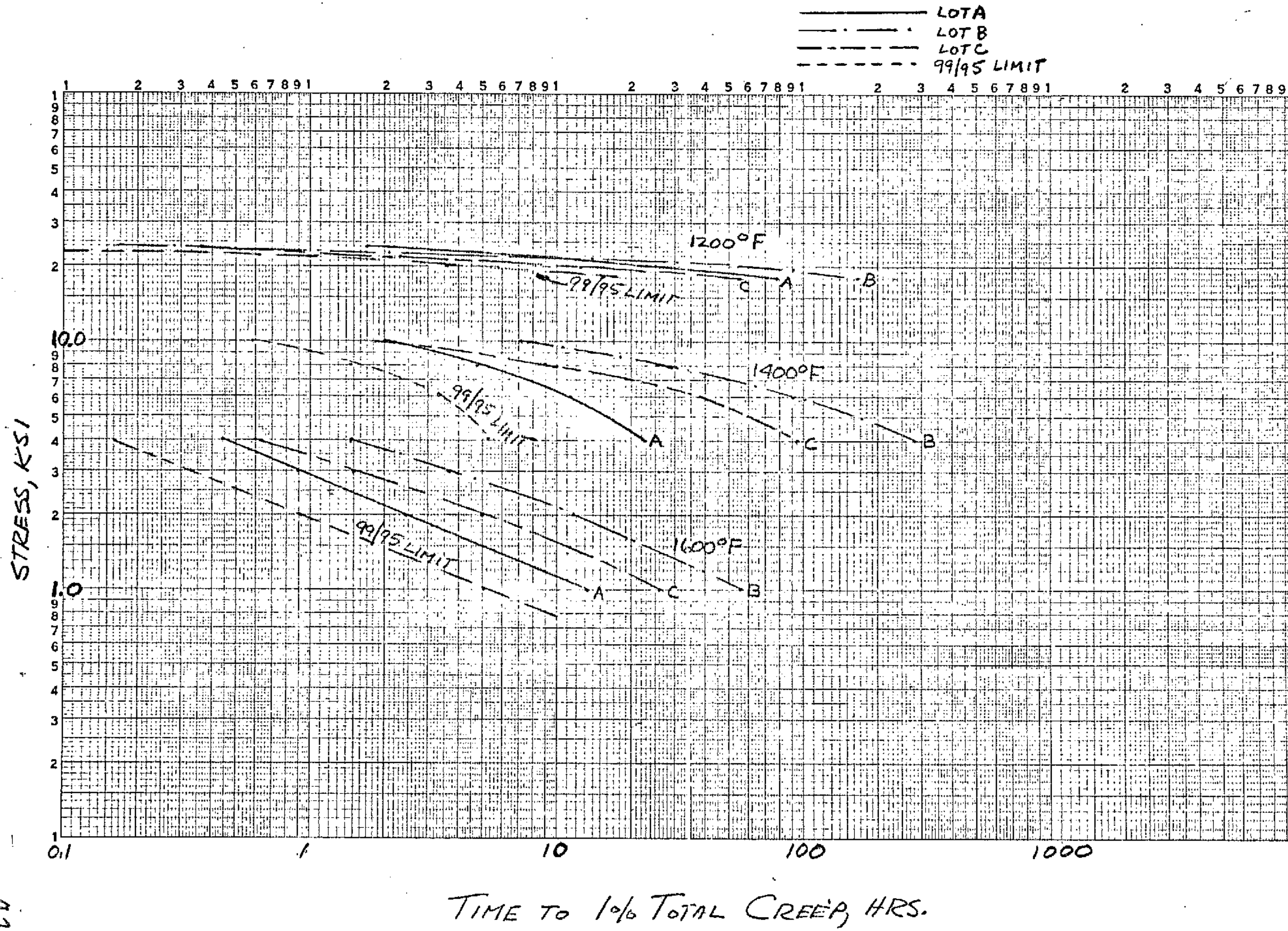

Figure 1

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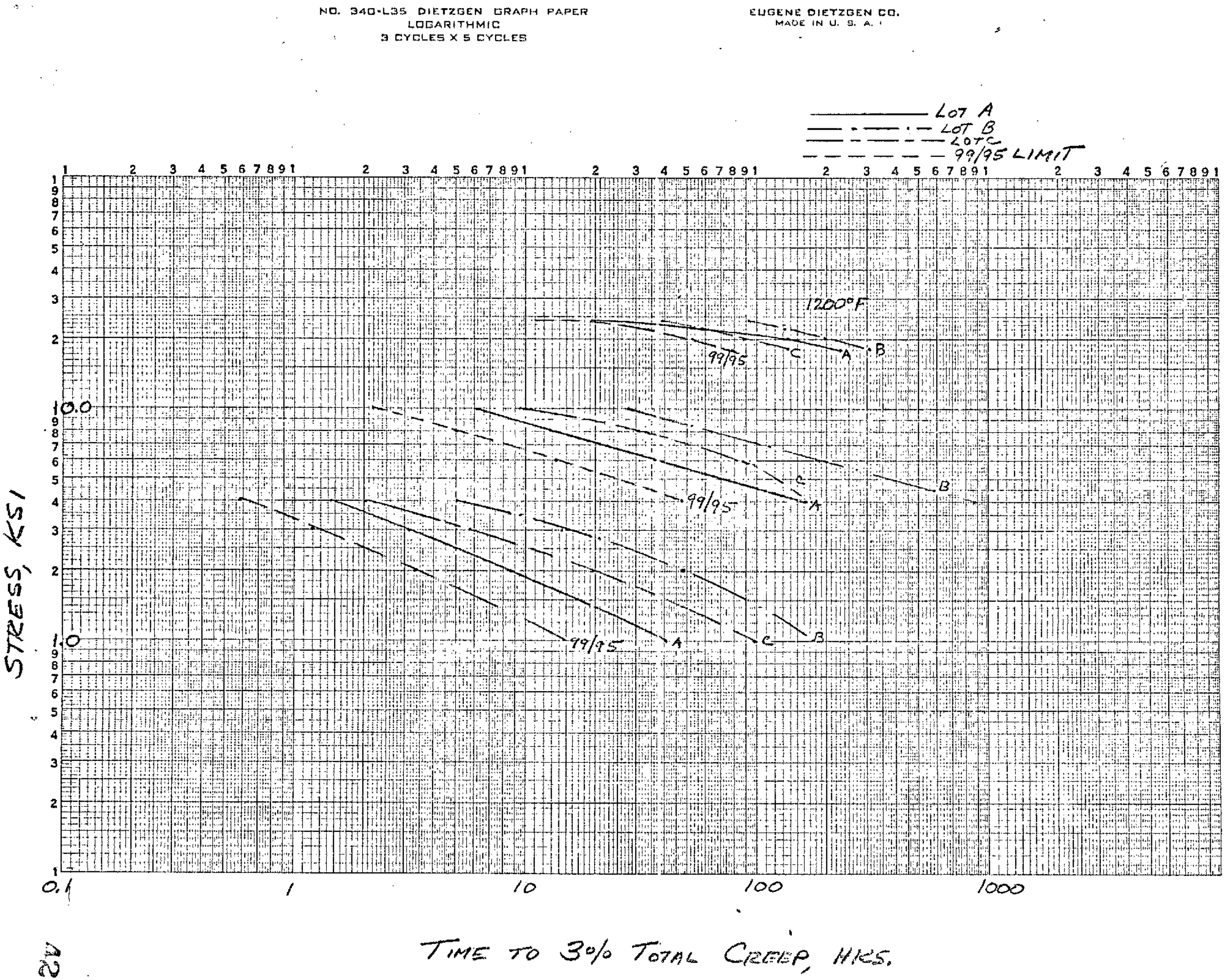

Figure 2

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AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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EXPLANATION OF SYMBOLS ON PAGES 2 - 4

s = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

PREPARED BY: M Shev

REVIEWED BY: [signature]

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 5/14/72

MATERIAL SS 347 FORM NOZZLE FORGING CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS QQ-S-763

PROPERTY NUMBER OF CYCLES TO VARIOUS K1 LEVELS

	LOG OF CYCLES						NUMBER OF CYCLES			
K1 KSI - $\sqrt{IN}$	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	50 % POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
30	4.062	.0408	3	5	5.24	3.848	11527	7050	C	1
40	3.470		5	5	5.10	3.262	2950	1828		
50	2.878		2	5	5.41	2.657	755	454		
60	2.286		1	5	5.85	2.047	193	112		

MATERIAL SS 347 FORM NOZZLE FORGING CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS QQ-S-763

PROPERTY CYCLIC FRACTURE TOUGHNESS, Ki, KSI $-\sqrt{IN}$

No. of Cycles	MEAN	s	n_e	f	k	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
1	75.2	4	-	-	-	63.0*	C	1
1000	47.9	0.71	3	5	5.24	44.2		
10000	31.0	0.73	3	5	5.24	27.2		

* CONSERVATIVE ENGINEERING ESTIMATE. NOT 99/95 DESIGN ALLOWABLE

MATERIAL SS 347 FORM NOZZLE FORGING CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS QQ-S-763

PROPERTY CRACK GROWTH RATE, da/dN, MICRO-INCHES PER CYCLE

	LOG (da/dN)						da/dN			
Ki KSI - √IN	MEAN	s	n_e	f	k	99/95 UPPER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
40	1.592	0.184	7	22	3.39	2.216	39	164	C	1
50	2.000		20	22	3.22	2.592	100	391		
60	2.480		20	22	3.22	3.072	302	1182		
70	2.989		10	22	3.32	3.601	976	3989		
80	3.507		5	22	3.48	4.150	3211	14136		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington, under ANSC P.O. N-01499.

One lot of SS 347 nozzle segment per QQ-S-763 (from NERVA Nozzle Forging S/N 880033) was used in the test program. Fracture toughness specimens were fabricated so as to maintain the flaw propagation direction of the specimens parallel to the forging direction. A total of 12 specimens were fabricated and testing was conducted at room temperature.

A total of 8 specimens were tested in GH_2 and 4 specimens were tested in GHe to note the effect of hydrogen on the toughness of the material. Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. The test matrix, giving the test conditions and number of specimens tested was as follows:

Test Type	Test Environment (1200 psig) GHe	GH_2
Static Fracture	1	2
Cyclic Fracture	3	6

From these results, a Ki versus number of cycles to failure curve was developed for each test condition. In addition, instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test.

The test results were as follows:

Specimen Number	Test Environment	No. of Cycles	Ki KSI - IN
880039	GH_2	1	63.3
880040	GHe	1	79.1
880049	GH_2	1	79.9
880050	GH_2	1	78.7
880043	GHe	298	56.5
880041	GHe	4902	42.3
880042	GHe	16537	35.5
880045	GH_2	355	56.5
880044	GH_2	2720	39.9
880047	GH_2	2575	40.5
880046	GH_2	5558	34.9
880048	GH_2	4856	35.7
880050	GH_2	30026	24.3

As seen from this table, one of the specimens, 880050, generated a static test observation in addition to a cyclic test. In addition, instantaneous crack growth data were supplied by Boeing on computer printouts, up to 7 pairs of observations (da/dN vs Ki) per specimen.

2. DATA ANALYSIS

a. Fracture Toughness

The four static fracture toughness tests failed to yield valid K_{IC} data. Instead they are reported as a special case of Ki, at one cycle. There was no appreciable difference between the tests in helium and hydrogen; therefore they were combined.

Regression analysis, with the aid of the G.E. computer program MULFIT was used for the cyclic fracture toughness data. An attempt was made to use the static test results in the same regression equation, but no simple function was found which would fit the combined data without a large increase in the standard error of estimate. The one cycle data reported on Page 3 merely represent the average of the 4 static tests.* The standard deviation of 4 is a conservative estimate from other materials, and the design allowable shown is an engineering estimate (3-sigma) rather than a 99/95 limit.

A linear equation (Ki vs log cycles) was found to fit the data very well. However, to provide for an observed difference between test results

* One of these had a value of 63.3 KSI $-\sqrt{IN}$, far below the other three. While its exclusion as an outlier might be justified, it was retained and averaged with the other three in order to maintain a conservative average.

in hydrogen and helium, an extra variable, x_2, was introduced into the regression equation and assigned the values $x_2 = 0$ for hydrogen, $x_2 = 1$ for helium. The results were as follows:

n	Regression Equation *	s_e**	R^2
9	$\log N = 5.837 - .05919\, x_1 + 1.3595\, x_2 - .92426\, x_1 x_2$	.0408	.996

* N = number of cycles; x_1 = Ki, x_2 = test environment.

** in logarithmic units.

This equation was used to calculate expected values of log N for various Ki levels from 30 to 60 KSI $-\sqrt{\text{IN}}$. By assigning $x_2 = 0$, the calculated values applied to the hydrogen environment, the worst case. The 99/95 lower limits were calculated in the usual manner and finally both expected values and limits were converted to anti-log units (number of cycles). To place the data in a more useful form, the equation was back-solved to yield expected and allowable Ki's for various numbers of cycles. These are given on Page 3. Results are shown graphically in Figure 1.

b. Crack Growth Rate (da/dN)

The data from the computer printouts were divided into two groups, below and above Ki = 65. These represent the two slopes of the lines relating log (da/dN) as a function of Ki. However there were insufficient data for Ki > 65 and only one of the linear slopes could be determined. A quadratic equation, however was found to fit the entire body of data well, and was used to calculate design allowables. The computer program MULFIT was used to determine the least squares regression lines. The analysis was done separately for the hydrogen and helium groups. The tests in hydrogen showed slightly higher crack growth rates at all Ki levels; therefore the regression equation for this group was the only one used. The linear equation for Ki $\leq$ 65 (Eq. 2) and the quadratic equation for the entire range (Eq. 1) were as follows:

	n	Regression Equation *	s_e*	R^2
Eq.1	25	$\log y = 23.559 - 30.608 \log x + 10.546 (\log x)^2$	.184	.888
Eq.2	19	$\log y = -5.946 + 4.697 \log x$	.125	.859

* y = da/dN, micro-inches per cycle; x = Ki

** in logarithmic units.

Equation 1 was used to calculate expected values of log (da/dN) for various Ki levels. Design allowables were then calculated in the usual manner. The results are plotted in Figure 2.

3. REFERENCES

(1) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

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CYCLIC FRACTURE TOUGHNESS OF SS 347, RT, GH_2 @ 1200 psi

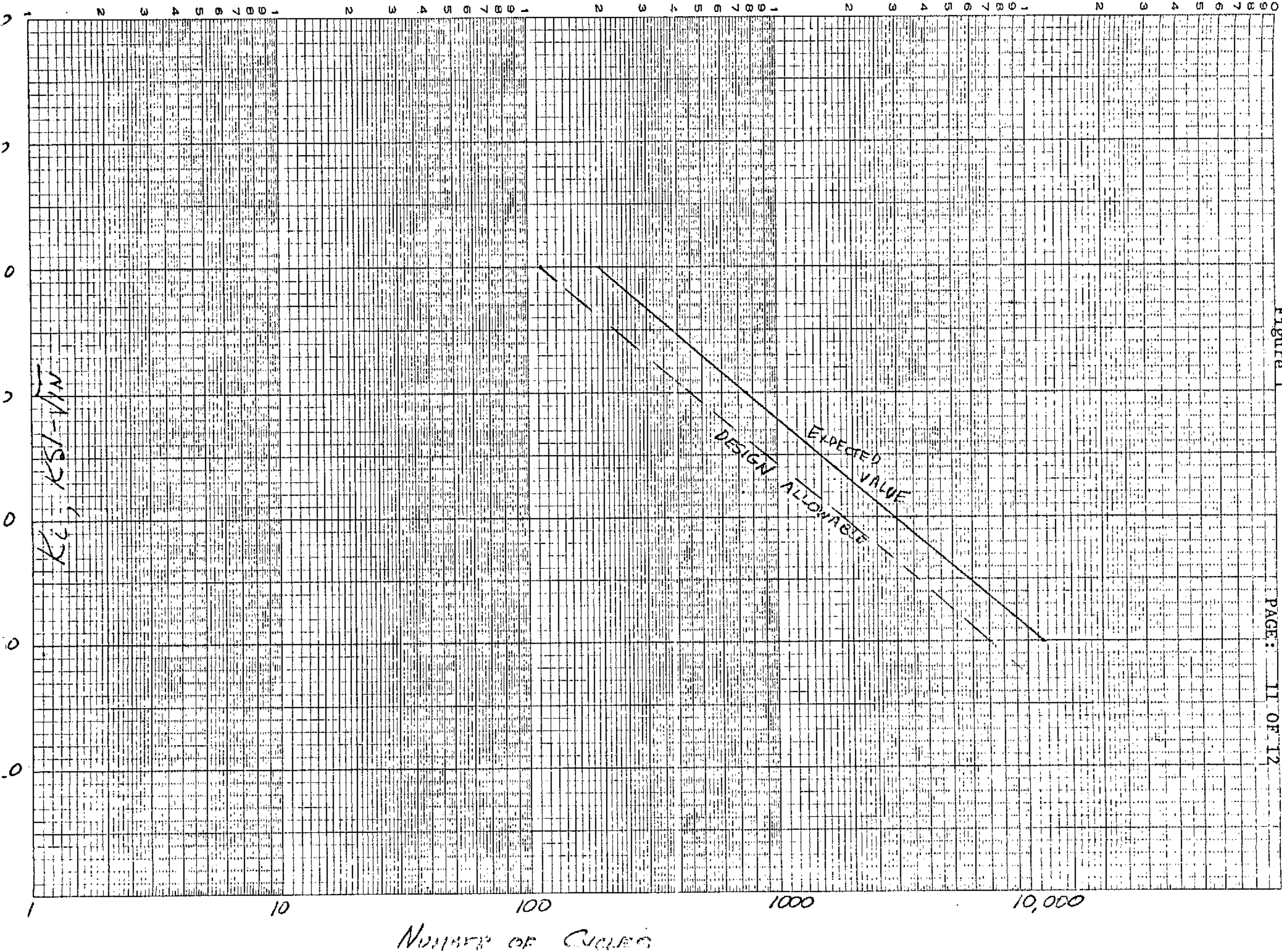

Figure 1

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CRACK GROWTH RATE OF SS 347, RT, GH_2 @ 1200 psi.

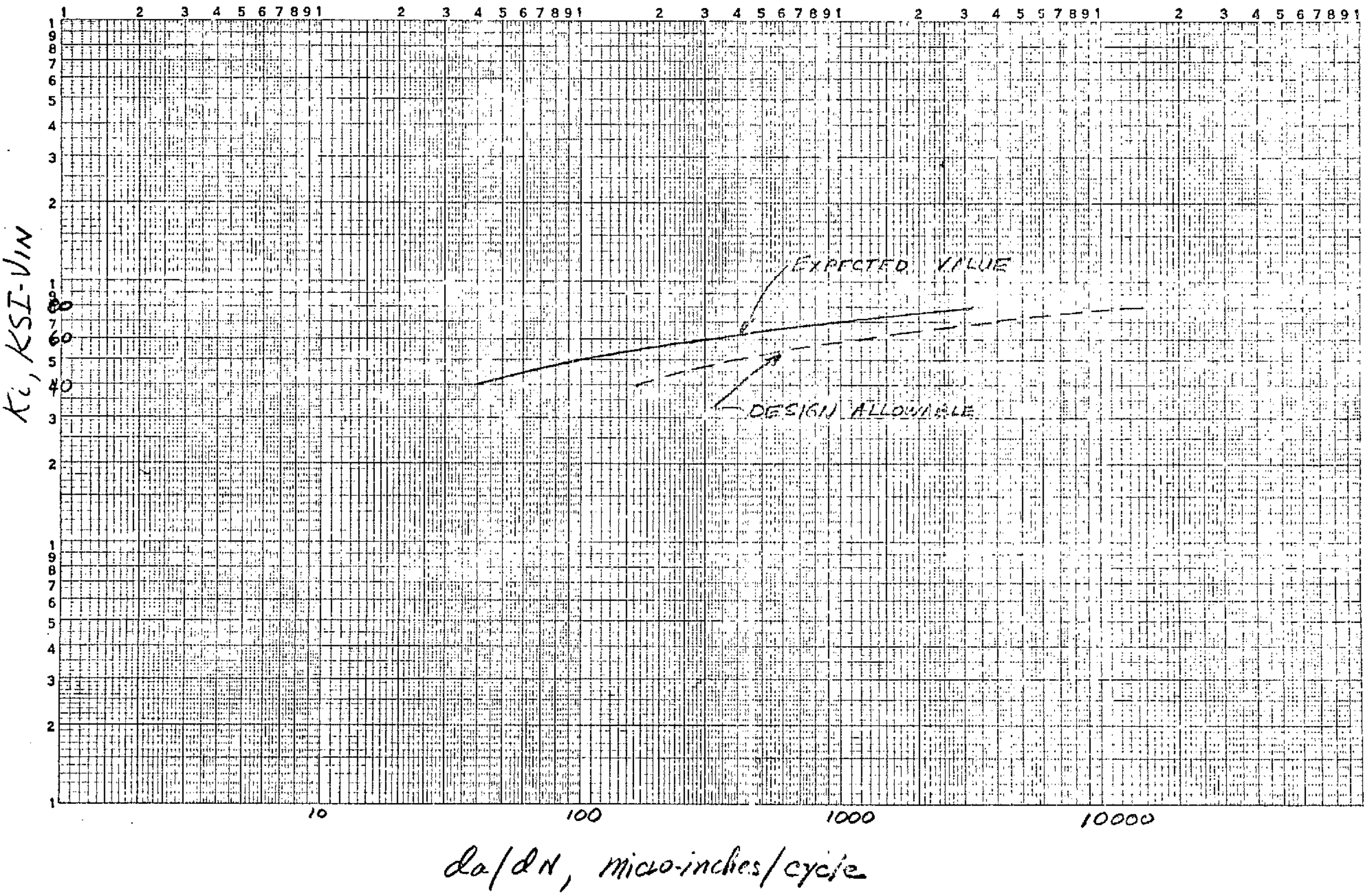

Figure 2

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AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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SYMBOLS USED ON PAGES 2 - 5

$\bar{X}$ = GROUP AVERAGES

n = SAMPLE SIZE ASSOCIATED WITH $\bar{X}$

f = DEGREES OF FREEDOM FOR POOLED WITHIN-GROUP STANDARD DEVIATION

k = 99/95 LOWER TOLERANCE LIMIT FACTOR FOR n AND f

s = POOLED WITHIN-GROUP STANDARD DEVIATION

PREPARED BY: M. J. Davidson

REVIEWED BY: M. Shev

CLASSIFICATION:

UNCLASSIFIED

PER M. J. Davidson

DATE 3/1/72

MATERIAL Al 7039 FORM FORGING CONDITION T-63

SPECIFICATIONS AGC 90181

PROPERTY TENSILE ULTIMATE STRENGTH, KSI, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)		$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
0									
4.3×10^{17}									
8.6×10^{17}	****	91.74	1.12	16	28	3.143	88.22	C	(1)
8.6×10^{17} + 540°R ANNEAL ***									
5.8×10^{18}		95.00	1.12	3	28	3.582	90.99	C	(1)
5.8×10^{18} + 340°R ANNEAL ***									
5.8×10^{18} + 540°R ANNEAL *	****	90.73	1.12	12	28	3.187	87.16	C	(1)
5.8×10^{18} + 540°R ANNEAL **									
5.8×10^{18} + 540°R ANNEAL ***									

* 10 MINUTES

** 100 MINUTES

*** 100 MINUTES

**** NO SIGNIFICANT DIFFERENCE AMONG GROUPS; THEREFORE DATA POOLED.

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

MATERIAL Al 7039 FORM FORGING CONDITION T-63

SPECIFICATIONS AGC 90181

PROPERTY TENSILE YIELD STRENGTH, KSI, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)		$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
0		76.94	1.27	5	24	3.448	72.56	C	(1)
3.4×10^{17} 8.6×10^{17}	****	85.40	1.27	8	24	3.325	81.18	C	(1)
8.6×10^{17} + 540°R ANNEAL ***		79.07	1.27	3	24	3.634	74.45	C	(1)
5.8×10^{18}		94.93	1.27	3	24	3.634	90.31	C	(1)
5.8×10^{18} + 340°R ANNEAL ***		89.87	1.27	3	24	3.634	85.25	C	(1)
5.8×10^{18} + 540°R ANNEAL *		85.00	1.27	3	24	3.634	80.38	C	(1)
5.8×10^{18} + 540°R ANNEAL ** 5.8×10^{18} + 5400R ANNEAL ***	****	83.30	1.27	6	24	3.395	78.99	C	(1)

* 10 MINUTES

** 100 MINUTES

*** 1000 MINUTES

**** NO SIGNIFICANT DIFFERENCE AMONG GROUPS; THEREFORE DATA POOLED

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

MATERIAL Al 7039 FORM FORGING CONDITION T-63

SPECIFICATIONS AGC 90181

PROPERTY ELONGATION, %, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)		$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
0									
3.4×10^{17}	****	12.02	1.26	16	27	3.157	8.04	C	(1)
8.6×10^{17}									
8.6×10^{17} + 540°R ANNEAL ***									
5.8×10^{18}		4.9	1.26	3	27	3.593	0.37	C	(1)
5.8×10^{18} + 340°R ANNEAL ***		9.0	1.26	3	27	3.593	4.47	C	(1)
5.8×10^{18} + 540°R ANNEAL *									
5.8×10^{18} + 540°R ANNEAL **	****	11.6	1.26	9	27	3.254	7.50	C	(1)
5.8×10^{18} + 540°R ANNEAL ***									

* 10 MINUTES

** 100 MINUTES

*** 1000 MINUTES

**** NO SIGNIFICANT DIFFERENCE AMONG GROUPS; THEREFORE DATA POOLED.

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

MATERIAL Al 7039 FORM FORGING CONDITION T-63

SPECIFICATIONS AGC 90181

PROPERTY FRACTURE TOUGHNESS, K_Q KSI- $IN^{1/2}$, @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)		$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
0 1.4×10^{18}	*	30.76	1.85	8	9	4.017	23.33	C	(1)
6.5×10^{18}		22.60	1.85	3	9	4.279	14.68	C	(1)

* NO SIGNIFICANT DIFFERENCE BETWEEN GROUPS; THEREFORE DATA POOLED

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

I. TEST DESCRIPTION (REFERENCE (1))

Tensile and fracture toughness specimens per AGC P/N 1134298 and 1137229 were prepared from Al 7039-T63 forging from Wyman-Gordon Heat No. B-260. The specimens were irradiated to three different fluence levels at 140°R in GTR-20C at Convair Aerospace Division/Fort Worth. One group of tensile specimens irradiated to the middle fluence was annealed at 540°R for 1000 minutes. In addition, groups of tensile specimens irradiated to the highest fluence were annealed at 340°R for 1000 minutes and 540°R for 10, 100 and 1000 minutes. The irradiated specimens and unirradiated control groups were tested at 140°R. The results of the tests are shown in the following tables in which each entry is the average of 3 or 4 or 5 specimens.

TENSILE TESTS

Fluence n/cm^2, E > 1 MeV	Post-Irradiation Anneal Temp, (°R)/Time,(Min)	No. of Specimens	Ultimate Strength (ksi)	Yield Strength (ksi)	Elongation %
0	None	5	91.5	76.9	12.4
3.4×10^{17}	None	4	92.1	85.0	11.7
8.6×10^{17}	None	4	91.5	85.8	11.0
8.6×10^{17}	540/1000	3	92.0	79.1	13.2
5.8×10^{18}	None	3	95.0	94.9	4.9
5.8×10^{18}	340/1000	3	89.9	89.9	9.0
5.8×10^{18}	540/10	3	90.4	85.0	11.3
5.8×10^{18}	540/100	3	90.6	83.5	12.2
5.8×10^{18}	540/1000	3	92.1	83.1	11.3

FRACTURE TOUGHNESS TESTS

Fluence n/cm^2, E > 1 MeV	No. of Specimens	K_Q $Ksi\text{-}in^{1/2}$
0	4	29.6
1.4×10^{18}	4	31.9
6.5×10^{18}	3*	22.6*

* One value was rejected as an outlier using Dixon Criterion at an α risk of 10%.

II. DATA ANALYSIS

Ultimate Strength

There was no statistically significant (at 95% confidence level) difference in ultimate strength of specimens irradiated to 6.8×10^{17} n/cm^2 or less. Therefore the data below this fluence were pooled for calculation of mean, and 99/95 lower limit. There was also no significant difference between annealed specimens irradiated to 5.8×10^{18} n/cm^2 and these data were also pooled for calculation of mean and 99/95 lower limit. The variances of all groups were homogeneous. Accordingly, all were pooled for calculation of a standard deviation.

Yield Strength

There was no statistically significant difference between yield strength of specimens irradiated to 3.4×10^{17} and 8.6×10^{17} n/cm^2 or between specimens irradiated to 5.8×10^{18} n/cm^2 and subsequently annealed at 540°R for 100 and 1000 minutes. Therefore these four groups were pooled into two groups for calculation of means and 99/95 lower limits. Annealing for 1000 minutes at 340°R and for 10 minutes at 540°R resulted in less recovery. Therefore, these groups are recorded separately. The variances of all groups were homogeneous and therefore, were pooled for calculation of a standard deviation.

Elongation

There was no significant difference in elongation of specimens irradiated to 8.6 X 10^{17} n/cm^2 or less. Therefore, the data from these groups were pooled for calculation of mean and 99/95 lower limit. Specimens irradiated to 5.8 X 10^{18} n/cm^2 showed a marked decrease in elongation with partial recovery when annealed at 340°R for 1000 minutes. These means and 99/95 lower limits groups are shown individually. Data from specimens irradiated to 5.8 X 10^{18} n/cm^2 and subsequently annealed at 540°R for 10, 100 and 1000 minutes are pooled because all showed complete recovery of elongation. The variances of all groups were pooled for calculation of a standard deviation.

Fracture Toughness

Unirradiated specimens and specimens irradiated to 1.4 X 10^{18} n/cm^2 showed no significant difference in fracture toughness. Accordingly, these data were pooled for calculation of mean and 99/95 lower limit. Specimens irradiated to 6.5 X 10^{18} n/cm^2 showed a decrease in fracture toughness and are shown separately. One value from this group was rejected as an outlier using Dixon Criterion[2] at an α risk of 10%. The variances of all groups were homogeneous and therefore pooled for calculation of a standard deviation. The fatigue cracks of approximately one half of the specimens were not valid for calculation of K_{Ic} per ASTM E-399, therefore the fracture toughness is recorded as K_Q even though there is good agreement between "valid" and "not valid" data.

III. REFERENCES

(1) General Dynamics, Convair Aerospace Division Report FZK-381, NERVA Irradiation Program, GTR-20C, Combined Effects of Reactor Radiation and Cryogenic Temperature on NERVA Structural Materials, May 1971.

(2) M. G. Natrella, Experimental Statistics, National Bureau of Standards Handbook 91, 1963, Page 17 - 3.

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

CONTENTS

THIS REVISION SUPERSEDES DRM 04.02 DATED 11-23-70. ROOM TEMPERATURE TEST DATA ON ANOTHER LOT OF MATERIAL HAVE BEEN INCLUDED, AND ACCORDINGLY THE DESIGN ALLOWABLES HAVE BEEN RE-CALCULATED. DATA AT THE OTHER TEMPERATURES ARE UNCHANGED. A NEW SECTION OF TEXT HAS BEEN ADDED TO DESCRIBE THE NEW TEST MATERIAL AND THE METHODS OF ANALYSIS.

PREPARED BY: M Shev

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 3/24/72

MATERIAL: Ti 5Al-2.5Sn (ELI) FORM: Pancake Forgings CONDITION: VACUUM ANNEALED

SPECIFICATIONS: AGC 90163, ANS 90297-2

PROPERTY: Ultimate Tensile Strength, ksi DIRECTION: Tangential, Radial

TEMP °F	DIRECTION	MEAN VALUE (ksi)	VARIANCE WITHIN-LOT	VARIANCE LOT-TO-LOT	VARIANCE COMBINED	COMBINED STANDARD DEVIATION s	m **	f ***	k	DESIGN ALLOWABLE (ksi)	df FOR WITHIN-LOT VARIANCE	DATA CATEGORY	SOURCE REFERENCE
****RT	TANGENTIAL AND RADIAL	116.3	2.36	–	–	1.54	6	4.0	3.24	111	40	A	1, 2, 3, 4
-320	TANGENTIAL	188.2	10.75*	1.72	12.47	3.53	8.0	12.3	3.72	175	36*	A	1, 2
-423	TANGENTIAL	210.6	12.40	0.94	13.35	3.65	21.9	19.8	3.26	199	28	A	2, 3

*POOLED FROM -320 AND -423°F DATA.
**m = EFFECTIVE SAMPLE SIZE USED IN DETERMINATION OF k.
***f = EFFECTIVE NUMBER OF DEGREES OF FREEDOM ASSOCIATED WITH s, USED IN DETERMINATION OF k.
**** REVISED ROOM TEMPERATURE DATA BASED ON INCLUSION OF FOURTH LOT (REFERENCE (4)). METHOD OF LOWEST LOT MEAN WAS USED. THE MEAN VALUE SHOWN IS FOR HEAT NO. 29272. THE VARIANCE WAS POOLED WITHIN ALL FOUR HEATS AND s IS THE SQUARE ROOT OF THIS VARIANCE.

MATERIAL: Ti 5Al-2.5Sn (ELI) FORM: Pancake Forgings CONDITION: VACUUM ANNEALED

SPECIFICATIONS: AGC 90163, ANS 90297-2

PROPERTY: Yield Tensile Strength, ksi DIRECTION: Tangential, Radial

TEMP °F	DIRECTION	MEAN VALUE (ksi)	VARIANCE WITHIN-LOT	VARIANCE LOT-TO-LOT	VARIANCE COMBINED	COMBINED STANDARD DEVIATION s	m **	f ***	k	DESIGN ALLOWABLE (ksi)	df FOR WITHIN-LOT VARIANCE	DATA CATEGORY	SOURCE REFERENCE
****RT	TANGENTIAL AND RADIAL	108.4	3.99	-	-	2.00	8.	40	3.16	102	40	A	1, 2, 3,
-320	TANGENTIAL	174.6	17.71*	3.71	21.42	4.63	7.5	11.0	3.82	157	33*	A	1, 2
-423	TANGENTIAL	190.6	20.25	3.73	23.98	4.90	15.9	12.8	3.60	173	25	A	2,3

*POOLED FROM -320 AND -423°F DATA.
**m = EFFECTIVE SAMPLE SIZE USED IN DETERMINATION OF k.
***f = EFFECTIVE NUMBER OF DEGREES OF FREEDOM ASSOCIATED WITH s, USED IN DETERMINATION OF k.
**** REVISED ROOM TEMPERATURE DATA BASED ON INCLUSION OF FOURTH LOT (REFERENCE (4)). METHOD OF LOWEST LOT MEAN WAS USED. MEAN VALUE SHOWN WAS FOR HEAT C1029. THE VARIANCE WAS POOLED WITHIN ALL FOUR HEATS AND s IS THE SQUARE ROOT OF THAT VARIANCE.

MATERIAL: Ti 5Al-2.5Sn (ELI) FORM: Pancake Forgings CONDITION: VACUUM ANNEALED

SPECIFICATIONS: AGC 90163, ANS 90297-2

PROPERTY: Elongation, % DIRECTION: TANGENTIAL, RADIAL

TEMP °F	DIRECTION		MEAN VALUE (%)	VARIANCE WITHIN-LOT	VARIANCE LOT-TO-LOT	VARIANCE COMBINED	COMBINED STANDARD DEVIATION s	m **	f ***	k	df FOR WITHIN-LOT VARIANCE	DESIGN ALLOWABLE (%)	DATA CATEGORY	REFERENCE SOURCE
****RT	TANGENTIAL AND RADIAL	LOG (ELONGATION)	1.136	.00222	-	-	.0471	24	40	2.98		0.996		1, 2, 3, 4
		ELONGATION →	13.7									9.9	A	
-320	TANGENTIAL	LOG (ELONGATION)	1.032	.00274*	.00415	.00689	.0830	4.2	3.9	5.88	36*	0.544		1, 2
		ELONGATION →	10.8									3.5	A	
-423	TANGENTIAL	LOG (ELONGATION)	1.190	.00246	.00085	.00331	.0575	13.1	9.8	3.86	28	0.968		2, 3
		ELONGATION →	15.5									9.3	A	
ALTERNATE METHOD FOR -320°F TO PRODUCE A HIGHER ALLOWABLE OF DATA CATEGORY "B"														
-320	TANGENTIAL	LOG (ELONGATION)	1.032	.00247	.00422 (ASSUMED UPPER BOUND)	-	-	-	-	-	8	0.780	B	1, 2
		ELONGATION →	10.8									6.0		

* POOLED FROM -320°F AND -423°F DATA.

** m = EFFECTIVE SAMPLE SIZE USED IN DETERMINATION OF k.

*** f = EFFECTIVE NUMBER OF DEGREES OF FREEDOM ASSOCIATED WITH s, USED IN DETERMINATION OF k.

**** REVISED ROOM TEMPERATURE DATA BASED ON INCLUSION OF FOURTH LOT (REFERENCE (4)) METHOD OF LOWEST LOT MEAN. THE MEAN VALUE SHOWN WAS FOR THE NEW LOT. THE VARIANCE WAS POOLED WITHIN ALL 4 HEATS, AND s IS THE SQUARE ROOT OF THAT VARIANCE.

I. TEST MATERIAL:

Three heats of billet stock meeting the chemical composition requirements of AGC Specification 90163 were tested. The sources, lot numbers and sizes of the forgings were as follows:

MILL SOURCE	FORGER	PANCAKE FORGING SIZE	HEAT (LOT) NUMBER
Titanium Metals Corp.	Wyman-Gordon Co.	17" dia x 10" high	K1029
Reactive Metals	Carlton Forge Co.	14" dia x 6" high	293722 and 294245

Tensile tests were conducted by the forger at room temperature and by AGC at -320 and -423°F. The room temperature specimens were equally divided between radial and tangential orientations; the cryogenic temperature specimens were tangential only. Tensile test data were available for the following numbers of specimens:

TEMPERATURE, °F	LOT NUMBER K1029	293722	294245
RT (Tangential)	4	3	3
RT (Radial)	4	3	3
-320 (Tangential)	3	4	4
-423 (Tangential)	26*	4*	2*

*Variation in sample size occurred from property to property at -423°F because of test anomalies.

II. DATA ANALYSIS:

The three lots were assumed to be a random sample from a normally distributed population of possible lots. The variance associated with a sample of this material from some unknown lot contains both a within-lot and a lot-to-lot component.

Within-lot variances were found to be homogeneous within temperature groups for all properties according to the Bartlett-Box test at the 0.10 significance level. In most cases, within-lot variances were also homogeneous across all temperature groups.

The data were analyzed according to the methods of Reference (4), paragraph 5.4.5.4. Because of the unequal sample size for the different lot/temperature combinations, the temperatures were treated separately; however, within-lot variances were sometimes pooled over more than one temperature if such pooling was both warranted by the homogeneity test and needed to obtain the 15 degrees of freedom required for category "A" data.

The logarithmic transform of elongation was used in the calculations in order to normalize the data and thus to develop more realistic design allowables.* Within the room temperature data, there was significant difference between orientations for elongation, and, therefore, the two orientations are reported separately. For yield and ultimate, no such differences were found; therefore the data for the two directions were combined.

The components of variance and the quantities m (effective sample size) and f (degrees of freedom associated with the combined variance) were computed with the aid of "SATT," a newly-written computer program on the G.E. Mark II Time-Sharing system. The 99/95 tables of Reference (b) were entered with m and f to obtain (by interpolation) the appropriate tolerance limit factors, k. Design allowables were then calculated as $\bar{X}$ - ks, and have been categorized as "A" data.

The allowable elongation at -320°F was 3.5%. This low value is in part a consequence of the high k (5.88) which is, in turn, a result of the relatively large lot-to-lot variation and the small number of lots. To provide a possibly more useful design allowable, an alternate method, per paragraph 5.8.3.1 of Reference (4), was used. It was assumed that the upper bound of the lot-to-lot variance of log elongation at -320°F was equal to the variance calculated from the data, viz. .0042. The design allowable thus calculated was 6.0% and is classified as category "B".

*Calculations using the untransformed elongation led to a design allowable of zero at -320°F.

SUPPLEMENT FOR R1 REVISION

Another group of room temperature data was made available (Reference (6)) and the purpose of this revision is to update the original DRM by combining this new information with the old.

The new data consists of the results of 24 tensile tests on 8" diameter pancake forgings made from TMCA Heat No. K8930. Forgings of two different thicknesses, 4.43" and 2.93" respectively, were made. The heat treatment was per ANS-90297-2 (1400°F vacuum-anneal) which is substantially the same heat treatment as was used in the earlier forgings (per AGC 90163).

Three forgings of each size were tested, with four tensile specimens from each, three radially and one tangentially oriented.

Summarized test results were as follows:

P/N	THICKNESS	S/N	DIRECTION	ULTIMATE* STRENGTH, KSI	YIELD* STRENGTH, KSI	ELONGATION* %
1138579-1	4.43"	3	Radial	117.7	109.3	12.3
			Tang.	121	114	15
"	"	4	Radial	117.7	110.0	13.3
			Tang.	118	108	13
"	"	5	Radial	118.0	110.7	14.3
			Tang.	120	114	16
1138579-2	2.93"	3	Radial	120.0	112.3	14.3
			Tang.	121	111	12
"	"	4	Radial	119.7	113.3	13.7
			Tang.	118	110	15
"	"	5	Radial	118.0	110.3	12.3
			Tang.	120	113	18

* For radial specimens, figures given are averages of three; for tangential specimens, the figures are for a single specimen.

Analysis of variance showed that for all three tensile properties, there were no significant differences between directions, forgings (within configuration), or configurations. Accordingly all data for this lot were pooled into a single sample of 24 specimens. Averages and standard deviations for this lot and the previous lots were:

HEAT NO.	n	UTS $\bar{\bar{X}}$	UTS s	YTS $\bar{\bar{X}}$	YTS s	LOG* ELONG $\bar{\bar{X}}$	LOG* ELONG s
TMCA K1029	8	120.2	1.67	108.4	1.92	1.196	.0360
RMI 293722	6	116.3	1.47	108.5	2.35	1.220	.0464
RMI 294245	6	118.5	1.97	111.2	2.23	1.168	.0597
TMCA K8930	24	118.8	1.44	111.2	1.88	1.136	.0472

This table shows that the average properties of the new lot are entirely consistent with the other three, and also that the variances are homogeneous. This latter observation was confirmed by the Bartlett-Box test, and the within-lot variances were pooled.

A change in data analysis guidelines took place between the issue of the original DRM and this revision. (Reference (7)). According to the revised version of TD 69-28, a minimum of 8 lots are required for the use of the primary method of Reference (4); previously only two lots were required. The

* The logarithmic transform of elongation was used in order to be consistent with the earlier DRM in which its use was required to avoid zero or negative design allowables.

new rule specifies that one of the alternate methods of Section 5.8, Reference (4), should be used with less than 8 lots. Accordingly, the method of the Lowest Lot Mean was used to develop design allowables from the 4-lot room temperature data. These design allowables were calculated as $\bar{X}_L$-ks where $\bar{X}_L$ is the lowest of the four lot means, s is the pooled within-lot standard deviation, and k is the 99/95 tolerance limit associated with m and f which are based on $\bar{X}_L$ and s. For elongation, the design allowable was calculated in the logarithmic form and then converted back to anti-log form.

Following the new guidelines, the data are categorized as "A". The data for -320°F and -423°F are unchanged in this revision.

III. <u>REFERENCES</u>

(1) NRO Materials Memorandum 69-131, P. P. Dessau to W. E. Campbell, Subject:"Evaluation of Large Ti 5Al-2.5Sn (ELI) and Alloy 718 Forgings", dated 18 September 1969.

(2) Fourth Quarterly Report, CY 1970, NERVA Materials Development.

(3) Second Quarterly Report, CY 1970, NERVA Materials Development.

(4) NERVA Program Procedure, R101, NRP-503, "Statistical Analysis of Materials Test Data".

(5) Owen, D. B., "Factors for One-Sided Tolerance Limits and for Variables Sampling Plans", Monograph No. SCR-607, Sandia Corporation (1963-1964).

(6) Memorandum N8130:0220, P. P. Dessau to H. Derow, dated 2 November 1971, Subject: "Pancake Forged Ti 5Al-2.5Sn ELI Data from TPA S/N 1".

(7) Letter L. C. Corrington (SNPO-C) to W. O. Wetmore (ANSC) dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data".

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MATERIALS DATA RELEASE

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* PROVIDED THAT CRYSTALLINE ISOTROPY OF MATERIAL IS MAINTAINED.

NOTE: THIS REVISION SUPERSEDES DRM 04.07 DATED 24 NOVEMBER 1971. DYNAMIC MODULUS HAS BEEN ADDED.

PREPARED BY: M Slev

REVIEWED BY

MATERIALS [illegible]

RELIABILITY [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Slev

DATE 3/24/72

MATERIAL Ti 5Al-2.5Sn ELI FORM ALL CONDITION ALL

SPECIFICATIONS. AGC 90163A DIRECTION ALL

PROPERTY LINEAR THERMAL EXPANSION, %

TEMP. °F	NOMINAL * VALUE	STANDARD DEVIATION s	k ***	99/95 LIMITS **		DATA CATEGORY	SOURCE REFERENCE
-300	-0.1442	.00280	2.576	-0.1370	-0.1514	C	1
-250	-0.1317	.00256		-0.1251	-0.1383		
-200	-0.1153	.00224		-0.1096	-0.1211		
-150	-0.0966	.00187		-0.0918	-0.1014		
-100	-0.0764	.00148		-0.0726	-0.0803		
- 50	-0.0553	.00107		-0.0526	-0.0581		
0	-0.0331	.00064		-0.0315	-0.0348		

* PERCENT CHANGE IN LENGTH FROM 68°F

** NOMINAL ± 5%

*** BASED ON NORMAL CURVE (INFINITE DEGREES OF FREEDOM)

MATERIAL Ti 5Al-2.5Sn ELI FORM ALL CONDITION ALL

SPECIFICATIONS AGC 90163A DIRECTION ALL

PROPERTY MEAN COEFFICIENT OF THERMAL EXPANSION (α), IN/IN/°F X 10^6

TEMP. °F	NOMINAL VALUE	s	k**	99/95 LIMITS *		DATA CATEGORY	SOURCE REFERENCE
FROM 68 TO -300	3.92	0.076	2.576	3.72	4.12	C	1
FROM 68 TO -250	4.14	0.080		3.93	4.35		
FROM 68 TO -200	4.30	0.083		4.09	4.52		
FROM 68 TO -150	4.43	0.086		4.21	4.65		
FROM 68 TO -100	4.55	0.089		4.32	4.78		
FROM 68 TO - 50	4.69	0.091		4.46	4.92		
FROM 68 TO 0	4.87	0.095		4.63	5.12		

* NOMINAL ± 5%

** BASED ON NORMAL CURVE (INFINITE DEGREES OF FREEDOM)

MATERIAL Ti 5Al-2.5Sn ELI FORM ALL CONDITION ALL

SPECIFICATIONS AGC 90163A DIRECTION ALL

PROPERTY THERMAL CONDUCTIVITY, BTU/HR-FT^2- °F

TEMP. °F	NOMINAL VALUE	STANDARD DEVIATION s	k **	99/95 LIMITS*		DATA CATEGORY	SOURCE REFERENCE
-250	3.29	.128	2.576	2.96	3.62	C	2
-225	3.41	.133		3.07	3.76		
-200	3.53	.137		3.18	3.89		
-175	3.65	.142		3.28	4.02		
-150	2.77	.146		3.39	4.14		
-125	3.88	.151		3.49	4.27		
-100	3.99	.155		3.59	4.39		
-75	4.10	.159		3.69	4.51		
-50	4.21	.163		3.79	4.63		
-25	4.31	.167		3.88	4.74		
0	4.42	.171		3.97	4.86		
25	4.52	.175		4.07	4.97		
50	4.62	.179		4.16	5.08		
75	4.72	.183		4.24	5.19		
100	4.81	.187		4.33	5.29		
125	4.91	.190		4.42	5.40		
150	5.00	.194		4.50	5.50		
175	5.09	.198		4.58	5.60		

* NOMINAL ± 10%

** BASED ON NORMAL CURVE (INFINITE DEGREES OF FREEDOM)

MATERIAL Ti 5Al-2.5Sn ELI FORM ALL CONDITION ALL

SPECIFICATIONS AGC 90163A DIRECTION ALL

PROPERTY DYNAMIC MODULUS, psi X 10^6

TEMP.	NOMINAL VALUE	STANDARD DEVIATION	k**	99/95 LIMITS*	DATA CATEGORY	SOURCE REFERENCE
RT	18.05	0.35	2.576	17.1 TO 19.0	C	4

* NOMINAL ± 5%

** BASED ON NORMAL CURVE (INFINITE DEGREES OF FREEDOM)

I. TEST DESCRIPTION

Ti 5Al-2.5Sn ELI specimens were submitted to Battelle Memorial Institute for the purpose of measuring the thermal expansion and the thermal conductivity. The specimens were obtained from an annealed pancake forging produced by Wyman-Gordon (P. O. 102554) from TMCA Heat K-1029.

Measurement of physical properties was conducted by BMI under ANSC P. O.'s N-900078 and 900079. The measurement techniques and results are reported in References 1 and 2.

Two specimens were submitted for each test, one each in the radial and tangential orientations with respect to the forging. Thermal expansion was measured from -320°F to room temperature on the two specimens and the series of measurements was repeated on the radial specimen. Thermal conductivity was measured on the two specimens in the approximate temperature range from -250° to 200°F.

II. DATA ANALYSIS

A. THERMAL EXPANSION

There were three complete sets of data, one on the tangential specimen and two on the radial specimen. Regression equations were fitted to each set by means of the computer program MULFIT*** on the G.E. computer. In these equations the independent variable was temperature change, ΔT, and thermal expansion in percent was the dependent variable. A fourth degree polynomial proved to be a satisfactory regression model for all three data sets.

The base temperature was 82°F for the tangential specimen and 68° and 72°F for the two runs on the radial specimens. In order to compare the regression equations it was necessary to put all three on a common temperature base. 68°F was selected and the data were adjusted so that ΔT was zero at this temperature for all three runs. New regression equations were computed, and expected thermal expansion values were calculated from the equations at 50° intervals from -300° to 0°F, resulting in the following table:

TEMPERATURE °F	LINEAR EXPANSION, % (CHANGE FROM 68°F) TANGENTIAL	RADIAL RUN 1	RADIAL RUN 2
0	-.0324	-.0339	-.0331
- 50	-.0553	-.0560	-.0547
-100	-.0771	-.0769	-.0753
-150	-.0976	-.0973	-.0949
-200	-.1162	-.1166	-.1131
-250	-.1320	-.1337	-.1293
-300	-.1441	-.1462	-.1422

This table shows differences among all three columns; the two duplicate runs on the radial specimen differ from each other by at least as much as either one differs from the tangential. Therefore there is no evidence that there is any difference between the two specimens other than that due to measurement error. Accordingly, the three columns were averaged at each temperature to yield the nominal values shown on Page 2. The upper and lower limits were calculated as these nominals $\pm$ 5%, which has been recommended (Reference 3) as a reasonable uncertainty band for those physical properties which exhibit little or no material variability.*

The mean coefficients of thermal expansion shown on Page 3 were obtained by dividing both the nominals and the limits on Page 2 by the temperature difference (ΔT).

* These limits have been designated "99/95 Limits" although there is no quantitative basis for this designation.

The k-value, 2.576, on Pages 2 and 3 is the 2-sided 99% normal curve value (or the tolerance limit factor for infinite degrees of freedom). The standard deviations, s, were obtained by dividing the difference between the limit and the nominal at each temperature by k.

B. THERMAL CONDUCTIVITY

A regression model was fitted to the data by means of the MULFIT*** program. A simple quadratic model fitted the data well. While there was some difference between the equations for the two specimens, it was impossible to tell whether this was a material difference, directional or otherwise, or merely a consequence of measurement error. On the basis that these forgings had not exhibited anisotropy in other properties, the results of the two directions were averaged to produce the nominal values on Page 4. An uncertainty band of ± 10% about the nominal values was established.* This band is considered to include both errors of measurement and material variability.

A tolerance limit factor, k, of 2.576 was again used and the standard deviation calculated in the same manner as for thermal expansion.

C. GENERAL

The data are categorized as "C". Although the measurements were made on specimens prepared from annealed forgings, the expansion data may be applied to any form or condition of the alloy consistent with reasonable isotropy. Thermal conductivity data similarly applies to all forms, but to the annealed condition only.

* See Footnote, Page 8.

SUPPLEMENT FOR REVISION 1 (REFERENCE (4))

Young's modulus was determined dynamically at ANSC on a radial specimen and a tangential specimen of a Ti-5Al-2.5Sn ELI pancake forging at room temperature. The specimens were obtained from an annealed pancake forging produced by Wyman-Gordon (P. O. 102554) from TMCA Heat K-1029.

The results given below indicate little or no anisotropy in the forging between the radial and tangential direction.

$$E \text{ radial} = 18.1 \times 10^6 \text{ psi}$$

$$E \text{ tangential} = 18.0 \times 10^6 \text{ psi}$$

The upper and lower limits were calculated as the average of these measurements $\pm$ 5%, per Reference (3)*. The k-value and the standard deviation were obtained in the same manner as for the other properties (See top of Page 9).

* See Footnote, page 8.

III. REFERENCES

1. Battelle Memorial Institute, Final Report on Linear Thermal Expansion Measurements of Stainless Steels, Aluminum and Titanium Alloys, dated 3 November 1970. (Work performed under ANSC P. O. No. N-900079).

2. Battelle Memorial Institute, Final Report on Thermal Conductivity and Electrical Resistivity Measurements of Stainless Steel, Aluminum and Titanium Alloys (ANSC P.O. No. N-900078).

3. Letter 7732:ML70-343, ANSC to SNPO-C dated 21 September 1970, Subject: Material Properties Data Book Meeting, SNPO-C, 18-19 August 1970.

4. Materials Memorandum N8130:0053, from A. J. Giannuzzi to M. S. Lev dated 8 March 1972, Subject: "Dynamic Modulus of Ti 5Al-2.5Sn ELI at Room Temperature".

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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PREPARED BY: M J Davidson

REVIEWED BY: M Sher

CLASSIFICATION:

UNCLASSIFIED

PER: M J Davidson

DATE: 28 March 1972

MATERIAL Ti 5Al-2.5Sn ELI FORM DIE FORGINGS CONDITION ANNEALED

SPECIFICATIONS AGC 90163A

PROPERTY FRACTURE TOUGHNESS, K_{Ic}, KSI - $IN^{1/2}$ @ 80°F

$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
98.8	4.6	9	7.3	4.143	79.8	C	(1)

SYMBOLS

$\bar{X}$ = GROUP AVERAGES

n = SAMPLE SIZE ASSOCIATED WITH $\bar{X}$

f = DEGREES OF FREEDOM FOR POOLED WITHIN-GROUP STANDARD DEVIATION

k = 99/95 LOWER TOLERANCE LIMIT FACTOR FOR n AND f

s = POOLED WITHIN-GROUP STANDARD DEVIATION

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I. TEST DESCRIPTION

One inch thick fracture toughness specimens per AGC P/N 1138365-104 "D" were prepared from die forged Ti 5Al-2.5Sn ELI. The forgings were from TMCA Billet "B", Heat K8930 and RMI Billet "T", Heat 804722. One specimen was made from each of several ring sections with the crack growing in the radial direction. The specimens were manufactured by Farrar Grinding Company, Inc., Inglewood, California and tested by Metallurgical Testing Corporation, City of Industry, California. The results of the tests are shown in the following table in which each entry is the average of 4 or 5 specimens.

Mill Source	No. of Specimens	Fracture Toughness ksi - $In^{1/2}$
TMCA	4	99.4
RMI	5	98.2

II. DATA ANALYSIS

There was no significant difference in fracture toughness between the two mill sources and the variances of the two groups were found to be homogeneous. Since the mill sources are construed as a fixed variable, the data from both mills could be pooled for calculation of mean, standard deviation and 99/95 lower limit per Reference (2).

III. REFERENCES

(1) Metallurgical Testing Corporation Test Report, Laboratory No. 12-109F, 18 January 1972

(2) Letter, M&S:JJL, L. C. Corrington to W. O. Wetmore dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data, Enclosure (1), Paragraph 4."

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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* PANCAKE FORGINGS @ -423°F ONLY

** RT IN GH_2, 100 PSI; -160°F IN GH_2, 1200 PSI; -423°F IN LH_2

NOTE: THIS REVISION SUPERSEDES DRM 04.10 DATED 30 MARCH 1972, WHICH INCLUDED ONLY STATIC FRACTURE TOUGHNESS AT ROOM TEMPERATURE. THE DATA INCLUDED IN THE ORIGINAL DRM HAS BEEN COMPLETELY INCORPORATED INTO THE REVISION.

EXPLANATION OF SYMBOLS ON PAGES 2 - 7:

- s = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)
- n_e = EFFECTIVE SAMPLE SIZE
- f = DEGREES OF FREEDOM FOR s
- k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

PREPARED BY: M Shev

REVIEWED BY:

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 5/4/72

MATERIAL Ti 5Al 2.5 Sn ELI FORM DIE FORGINGS/PANCAKE FORGINGS CONDITION ANNEALED

SPECIFICATIONS ANS 90297 B

PROPERTY FRACTURE TOUGHNESS, K_{IC}, KSI $\sqrt{IN.}$

A. DIE FORGINGS

TEMP °F	MEAN	s	n	f	k	99/95 DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
RT	100.0	4.23	12	12	3.67	84.5	C	1, 2
-160	85.4	4.23	2	12	4.20	67.6	C	2
-423	54.3	4.23	2	12	4.20	36.5	C	2

B. PANCAKE FORGINGS

TEMP °F	MEAN	s	n	f	k	99/95 DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-423	69.4	4.23	1	12	4.65	49.7	C	2

MATERIAL Ti 5Al 2.5Sn ELI FORM DIE FORGINGS CONDITION ANNEALED

SPECIFICATIONS ANS 90297 B

PROPERTY NUMBER OF CYCLES TO VARIOUS STRESS INTENSITY (Ki) VALUES

TEMP °F	Ki KSI-√IN	LOG OF CYCLES MEAN	s	k	n_e	f	99/95 LOWER LIMIT	NO. OF CYCLES 50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
RT	20	4.372	0.138	3.63	6	15	3.871	23528	7431	C	2
	30	3.922		3.53	10		3.435	8352	2722		
	40	3.501		3.48	14		3.021	3167	1049		
	50	3.108		3.49	13		2.626	1283	423		
	60	2.744		3.57	8		2.251	555	178		
	70	2.409		3.68	5		1.901	256	80		
	80	2.102		3.86	3		1.569	127	37		
-160	20	4.391		3.63	6		3.890	24594	7764	C	2
	30	3.920		3.51	11		3.436	8317	2727		
	40	3.478		3.46	16		3.001	3004	1001		
	50	3.064		3.49	13		2.582	1159	382		
	60	2.679		3.57	8		2.186	478	154		
-423	20	4.706		5.40	0.42*		3.961	50811	9137	C	2
	30	3.890		4.05	2		3.331	7774	2143		
	40	3.104		4.50	1		2.483	1270	304		

* NORMALLY, n_e IS ROUNDED TO THE LARGEST INTEGER NOT GREATER THAN THE CALCULATED VALUE. IN THIS CASE SUCH A ROUNDING PROCEDURE WOULD HAVE YIELDED n_e=0 FOR WHICH NO k VALUE WOULD EXIST. THEREFORE THE CALCULATED FRACTIONAL VALUE OF 0.42 WAS USED.

MATERIAL Ti 5Al 2.5Sn ELI FORM FORGINGS CONDITION ANNEALED

SPECIFICATIONS ANS 90297 B

PROPERTY CYCLIC FRACTURE TOUGHNESS (Ki) KSI-$\sqrt{IN}$

A. DIE FORGINGS

TEMP °F	NO. OF CYCLES	Ki (KSI -$\sqrt{IN}$) MEAN	s	n_e	f	k	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
RT	100	83.5	3.95	2	15	4.05	67.5	C	2
	1000	52.9	3.69	12	15	3.50	40.0	C	
	10000	28.2	3.44	9	15	3.55	16.0	C	
-160	1000	51.6	3.31	12	15	3.50	40.0	C	
	10000	28.3	2.92	10	15	3.53	18.0	C	
-423	1000	41.3	1.40	1	15	4.50	35.0	C	
	10000	28.6	1.58	2	15	4.05	22.2	C	

B. PANCAKE FORGINGS

TEMP °F	NO. OF CYCLES	MEAN	s	n_e	f	k	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-423	1000	46.2	1.40	1	15	4.50	39.9	D*	
	10000	33.6	1.58	1	15	4.50	26.5	C	

* SEE PAGE 15.

MATERIAL Ti 5Al 2.5Sn ELI FORM DIE FORGINGS CONDITION ANNEALED

SPECIFICATIONS ANS 90297 B

PROPERTY CRACK GROWTH RATE (da/dN), MICRO-INCHES/CYCLE @ RT

	LOG (CRACK GROWTH RATE)						CRACK GROWTH RATE			
Ki (KSI-√IN)	MEAN	s	n_e	f	k	99/95 UPPER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
20	0.696	.156	9	103	2.98	1.161	5	14	C	2
30	1.314		21		2.81	1.752	21	57		
40	1.751		46		2.73	2.177	56	150		
50	2.091		75		2.69	2.511	123	324		
60	2.369		74		2.69	2.789	234	615		
70	2.603		43		2.71	3.026	401	1061		
80	2.806		37		2.75	3.235	640	1718		
90	2.986		27		2.78	3.420	967	2628		
100	3.234		16		2.86	3.680	1708	4788		
110	3.504		26		2.78	3.938	3188	8663		
120	3.751		19		2.83	4.192	5636	15577		
130	3.979		10		2.95	4.439	9518	27942		
140	4.189		6		3.09	4.671	15461	46886		
150	4.385		4		3.24	4.890	24289	77703		

MATERIAL Ti 5A1-2.5Sn ELI FORM DIE FORGINGS CONDITION ANNEALED

SPECIFICATIONS ANS 90297 B

PROPERTY CRACK GROWTH RATE (da/dN), MICRO-INCHES/CYCLE @ -160°F, -423°F

		LOG (CRACK GROWTH RATE)						CRACK GROWTH RATE			
TEMP °F	Ki (KSI-√IN)	MEAN	s	n_e	f	k	99/95 UPPER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-160	30	1.045	.0887	6	41	3.23	1.331	11	21	C	2
	40	1.534		14		3.04	1.803	34	64		
	50	1.913		30		2.95	2.174	82	149		
	60	2.222		42		2.92	2.481	167	303		
	70	2.484		33		2.94	2.745	305	556		
	80	2.711		21		2.99	2.976	514	947		
	90	2.911		14		3.04	3.181	815	1516		
-423	30	1.171	0.327	5	16	3.64	2.361	15	230	C	2
	35	1.501		9		3.51	2.649	32	445		
	40	1.998		12		3.46	3.129	100	1347		
	45	2.601		11		3.47	3.736	399	5441		
	50	3.269		7		3.56	4.433	1858	27109		
	55	3.979		4		3.71	5.192	9533	155657		
	60	4.715		2		4.01	6.026	51984	1062360		

MATERIAL Ti 5Al-2.5Sn ELI FORM PANCAKE FORGINGS CONDITION ANNEALED

SPECIFICATION ANS 90297 B

PROPERTY CRACK GROWTH RATE (da/dN), MICRO-INCHES/CYCLE @ -423°F

	LOG (CRACK GROWTH RATE)						CRACK GROWTH RATE			
Ki (KSI-$\sqrt{IN}$)	MEAN	s	n_e	f	k	99/95 UPPER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
30	0.378	.327	2	16	4.01	1.689	2	49	C	2
35	0.707		3		3.82	1.956	5	90		
40	1.204		4		3.71	2.417	16	261		
45	1.807		6		3.59	2.981	64	957		
50	2.475		6		3.59	3.649	299	4456		
55	3.185		6		3.59	4.359	1532	22852		
60	3.921		4		3.71	5.134	8339	136198		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington under ANSC P. O. N-01499. (Room temperature static fracture toughness data obtained by Metallurgical Testing Corporation under ANSC P. O. N-02243 is also included in this DRM and has been combined with the corresponding Boeing data. The Metallurgical Testing Corp. data was the subject of the original DRM 04.10 which is being superseded by this revision. Material from the same two lots were used in both programs).

Two heats of Ti 5Al-2.5Sn ELI per ANSC Specification ANS 90297B were used for the test program. Heat 804722 produced by RMI, was used to fabricate die forgings. Heat K8930, produced by TMCA, was used to fabricate both die and pancake forgings. These heats were specially prepared for ANSC. All forgings were produced by Arcturus Manufacturing Company, Oxnard, Calif.

Fracture toughness specimens were fabricated from the die and pancake forgings so as to maintain the flaw propagation direction of the specimens parallel to the radial direction. A total of 24 specimens were fabricated and the testing was conducted at room temperature, -160°F and -423°F. The room temperature and -160°F tests were conducted in GH_2 and GHe; the -423°F tests were conducted in LH_2. The 24 specimen test program was designed as an interim program to provide statistical data from which a major test program would be developed. The test matrix for the interim program was designed to be as small as possible consistent with this goal.

Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. One static test and two cyclic tests were performed for each of the die and pancake forgings. From the results, a Ki versus number of cycles to failure curve was developed at each temperature. In addition, instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test. The test matrix is shown in Table 1.

Test results were as follows:

Test Temp, °F	Specimen No.	No. of Cycles	K_{IC} or Ki (KSI - $\sqrt{IN}$)
RT	880471	1 (K_{IC})	108.4
	880486	1 "	104.7
	880489	1 "	97.4
	880472	191	75.9
	880473	393	56.3
	880473	24377	19.2
	880474	2719	44.2
	880487	1500	48.6
	880488	3517	35.1
	880488	22000	18.8
	880490	25926	19.2
	880491	100	83.8
	880491	1882	46.9

Test Temp, °F	Specimen No.	No. of Cycles	K_{IC} or Ki (KSI - $\sqrt{IN}$)
-160	880477	1 (K_{IC})	84.9
	880483	1 "	86.0
	880478	2738	42.3
	880479	9737	30.3
	880479	23502	22.3
	880484	2540	43.4
	880485	606	57.7
	880485	1926	44.8
-423	880476	1 (K_{IC})	55.2
	880480	1 "	53.4
	880492 *	1 "	69.4
	880475	1609	36.7
	880482	1601	36.7
	880481	12867	25.8
	880493 *	10347	33.6

* Pancake Forgings

TABLE 1

					NUMBER OF OBSERVATIONS								
					R.T. (100 PSI GH_2)			-160 (1200 PSI GH_2)			-423 (LH_2)		
MILL	FORGING P/N	SHAPE	S/N	SPECIMEN	STATIC	CYCLIC	CRACK GROWTH	STATIC	CYCLIC	CRACK GROWTH	STATIC	CYCLIC	CRACK GROWTH
TMCA	1138575	RING	8	880471	1								
TMCA	1138575	"	8	880472		1	15						
TMCA	1138575	"	8	880473		2	20						
RMI	1138575	"	12	880474*		1	16						
RMI	1138575	"	12	880475								1	3
RMI	1138575	"	12	880476							1		
TMCA	1138576	"	5	880477				1					
TMCA	1138576	"	5	880478					1	13			
TMCA	1138576	"	5	880485*					2	8			
RMI	1138576	"	6	880480							1		
RMI	1138576	"	6	880481								1	6
RMI	1138576	"	6	880482								1	4
TMCA	1138577	"	4	880479					2	16			
TMCA	1138577	"	4	880483				1					
TMCA	1138577	"	4	880484					1	12			
RMI	1138578	"	11	880486	1								
RMI	1138578	"	11	880487		2	16						
RMI	1138578	"	11	880488		2	19						
RMI	1138578	CENTER	11	880489	1								
RMI	1138578	"	11	880490		1	18						
RMI	1138578	"	11	880491		2	19						
TMCA	1138579 (PANCAKE)	SLICE	3	880492							1		
	"	"	4	880493								1	7
	"	"	5	880494								1**	-

* IN GASEOUS HELIUM; ALL OTHERS IN H_2 ** FAILED ON INCREASING LOAD; NO CYCLIC DATA OBTAINED

2. DATA ANALYSIS

a. Static Fracture Toughness

The Boeing K_{IC} data consisted of 3 tests at room temperature, two at -160°F, and three at -423°F. All specimens were prepared from die forgings except one at -423°F which was from a pancake forging.

Results on nine specimens tested at room temperature by Metallurgical Testing Corporation under ANSC P.O. N-02243 (Reference 1) were also included in this analysis. These specimens were prepared from the same two material lots as those tested by Boeing. There was no significant difference in fracture toughness between the two material lots and therefore the two groups were combined.

Despite the fact that the Metallurgical Testing specimens were tested in air, their fracture toughness did not differ significantly from that of the Boeing specimens, tested in hydrogen. The within-group variabilities were also homogeneous and the two groups were combined to form a single group of 12 observations at room temperature.

Within group variabilities were found to be homogeneous over all temperatures, and accordingly a pooled standard deviation, s, based on 12 degrees of freedom,was calculated. The design allowables at each temperature were calculated in the usual manner as $\bar{X}$ - ks.

The pancake forging specimen had a much higher K_{IC} than the die forging specimens, a result expected both from previous testing experience and from comparative microstructure. This difference is also seen in the cyclic tests and in the crack growth rate data. The K_{IC} for the pancake forging is shown separately. It was assumed that the pooled standard deviation calculated for die forgings would also apply to pancake forgings.

b. Cyclic Fracture Toughness.

The method of regression analysis was used for the cyclic Ki data, employing the G. E. computer program MULFIT. In this analysis, the cyclic life is expressed as a function of the stress intensity, Ki. Because of the small number of observations at each temperature, data for all three temperatures were included in a single regression equation in which temperature occurs as a second independent variable.

Theoretically, the static tests could be included in this same regression equation as the cyclic tests since K_{IC} is merely Ki after one cycle. However, no simple function could be found that would efficiently fit both groups of data and therefore the static data were handled separately as shown above. The use of the MULFIT program consisted of trying various functions of Ki, temperature and cycle life to determine a model which would fit the experimental data with a minimum standard error of estimate, s_e. The following results were obtained:

$n = 20$; $s_e = .138$ (log units); $R^2 = .959$

Regression Equation:

$$\text{Log } y - 5.277 = .0494\, x + 1.432 \times 10^{-4}\, x^2 + 42.378\, (1/_R) - 1.4539\, (x/R$$

where x = stress intensity (Ki), KSI $-\sqrt{\text{in.}}$

R = test temperature, °R

y = number of cycles.

This equation includes the quadratic function of Ki, the reciprocal function of temperature, and a final interaction term which expresses the differences in response for the three different temperatures.

The equation was used to calculate the expected number of cycles for various stress intensity levels at the three temperatures. These are shown on Page 3, both in log and anti-log form. The 99/95 lower limits were calculated as log y - ks, where the tolerance limit factor k is based upon the effective sample size, n_e, and the degrees of freedom, f, associated with s. Finally the lower limit was converted to the anti-log form.

Probably a more useful representation of the same data is given on Page 4. Here, the expected stress intensity after various numbers of cycles are shown, with corresponding design allowables. These values were obtained by back-solving the regression equation for both mean and lower limit. The standard deviations were then estimated by dividing the difference between the mean and lower limit by the appropriate value of k.

The specimens tested in helium showed no extreme deviations from their expected values and were included along with the specimens tested in hydrogen.

The pancake forging specimen (880493), tested at -423°F was substantially off the curve, with an actual Ki of 33.6 at 10^4 cycles compared with an expected value of 28.6. It is therefore shown separately on Page 4, and its design allowable was calculated by assuming the same standard deviation as the die forgings. The stress intensity for pancake forgings at 10^3 cycles was estimated by extrapolating from 10^4 parallel to the die forging curve, and the corresponding design allowable was again calculated by assuming the same standard deviation. Because of the extrapolation, this one data item has been downgraded to category "D".

c. Crack Growth Rate

(1) General

Instantaneous crack growth rates (da/dN) in Micro-inches per cycle were obtained during cyclic testing. Paired data for crack growth rate vs average Ki were provided by Boeing in the form of computer printouts. Up to 20 data points were given for each cyclic specimen.

The data are plotted on log-log paper in Reference 2. The growth rate increases with stress intensity in an approximately linear manner until, at about 90 KSI $-\sqrt{in}$, there is a fairly abrupt increase in the slope.

The relationship could be represented by a quadratic equation over the entire range or by two straight lines of different slopes, each representing a portion of the data. The latter model was selected because it provides a simpler and more useful regression equation.

The computer program MULFIT was used to perform regression analysis. Each temperature was handled separately.

(2) Room Temperature

At room temperature the specimen tested in helium exhibited a slightly slower crack growth than the specimens tested in hydrogen. The helium data were excluded from the analysis to provide a more conservative estimate for crack growth rate in hydrogen.

The data were divided into two groups to represent the two different slopes, and separate regression analysis runs made for the two groups A brief series of iterations was required to locate the boundary of the groups close to the intersection of the two regression lines. A reasonable boundary was located at 90 KSI $-\sqrt{\text{in.}}$

Regression analysis results for the two goups were:

	n	Regression Equation	s_e*	R^2
for $Ki \leq 90$:	80	$\log(da/dN) = -3.863 + 3.5045 \log(Ki)$	.1645	.918
for $Ki > 90$:	27	$\log(da/dN) = -9.861 + 6.5466 \log(Ki)$	.1251	.896

* in logarithmic units

The standard errors of estimate were found to be homogeneous for the two groups and were combined to obtain a pooled s_e of .156 based on 103 degrees of freedom.

The expected value of the log of growth rate was calculated from these two equations for a series of stress intensity levels. The upper 99/95 limits were determined as Expected Value + ks_e, where the k values correspond with calculated effective sample size and f = 103.

Finally both the expected values and the 99/95 limits were converted to anti-log form (micro-inches per cycle).

3. -160°F

At -160°F, data points in the upper slope region were few in number and were extremely erratic. Regression analysis was, of necessity, confined to the determination of a single straight line for the region of $Ki \leq 90$ KSI $-\sqrt{\text{in.}}$ The specimen tested in helium yielded results that were typical of the three specimens tested in hydrogen and therefore these results were included in the same analysis.

The results were:

	n	Regression Equation	s_e	R^2
for $K \leq 90$	43	log (da/dN) = -4.733 + 3.9115 log x	.0887	.968

The calculation of expected values and design allowables followed the procedure used for the room temperature data.

(4) -423°F

At -423°F the pancake forging specimen exhibited a substantially lower crack growth rate at all Ki levels in comparison with the die forgings. A change in slope is indicated in the vicinity of 45 KSI - $\sqrt{\text{in.}}$ for both forging types, but the number of data points is too small to determine the two separate regression lines for the purpose of calculating design allowables. As an alternate, the quadratic model was used over the entire data range. In this analysis, forging type was input as a dummy variable, x_2, which was assigned a value of zero for die forgings and of one for pancake forgings. This technique results in two regression lines having the same slopes but different intercepts.

The results were as follows:

n	Regression Equations*	s_e	R^2
20	$\log (da/dN) = 60.614 - 83.453 \log x_1 + 29.253 (\log x_1)^2 - .794 x_2$	.327	.901

For die forgings, $x_2 = 0$ and the last term drops out. For pancake forgings, $x_2 = 1$ and the last term becomes -.794 which may be combined with the intercept 60.614 to produce a curve parallel with the first.

The regression equation was used to determine expected growth rates and 99/95 design allowables in the same manner as the other two temperatures. Pancake and die forgings are listed separately.

* x_1 = Ki; x_2 = forging type.

Linear regression equations for the two slopes were also calculated and are presented for information even though they were not used for calculating design allowables. The division of the data is based on a boundary value for da/dN of 100 micro-inches/cycle.

da/dN	n	Regression Equation *	s_e	R^2
≤ 100	11	$-30.217 + 19.857 \log x_1 - 1.187\, x_2$	.409	.789
> 100	9	$-6.578 + 5.257 \log x_1 - .466\, x_2$	.083	.924

* x_1 = Ki (KSI $-\sqrt{in}$); x_2 = Forging Type (x_2 = 0 for Die, x_2 = 1 for Pancake)

(5) Plots

Crack growth rate curves for the three temperatures are presented in Figures 1 - 4. Both the expected values and design allowables are shown.

d. Data Categories

The data are all categorized as "C" except for one "D" entry discussed above. Although the sample sizes for crack growth rate data far exceed the requirements for "A" data, these represent multiple observations per specimen, rather than an adequate number of specimens.

The intent of the data analysis and classification procedures is to make adequate allowance for material variability. To be consistent with this intent, the number of specimens, rather than the total number of observations is the logical criterion.

In the few cases where the specimen matrix meets the requirements of TD-28, there is still insufficient representation of material lots and forging configurations for such factors to be investigated adequately, and allowances made for their effects. Therefore none of the data have been classified above category "C".

3. REFERENCES

(1) Metallurgical Testing Corporation Test Report, Laboratory No. 12-109F, 18 January 1972

(2) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

NO. 340-L35 DIETZGEN GRAPH PAPER
LOGARITHMIC
3 CYCLES X 5 CYCLES

EUGENE DIETZGEN CO.
MADE IN U. S. A.

Ti 5Al 2.5Sn ELI
Die Forgings

CRACK GROWTH RATE @ ROOM TEMPERATURE (GH_2, 100 PSIG)

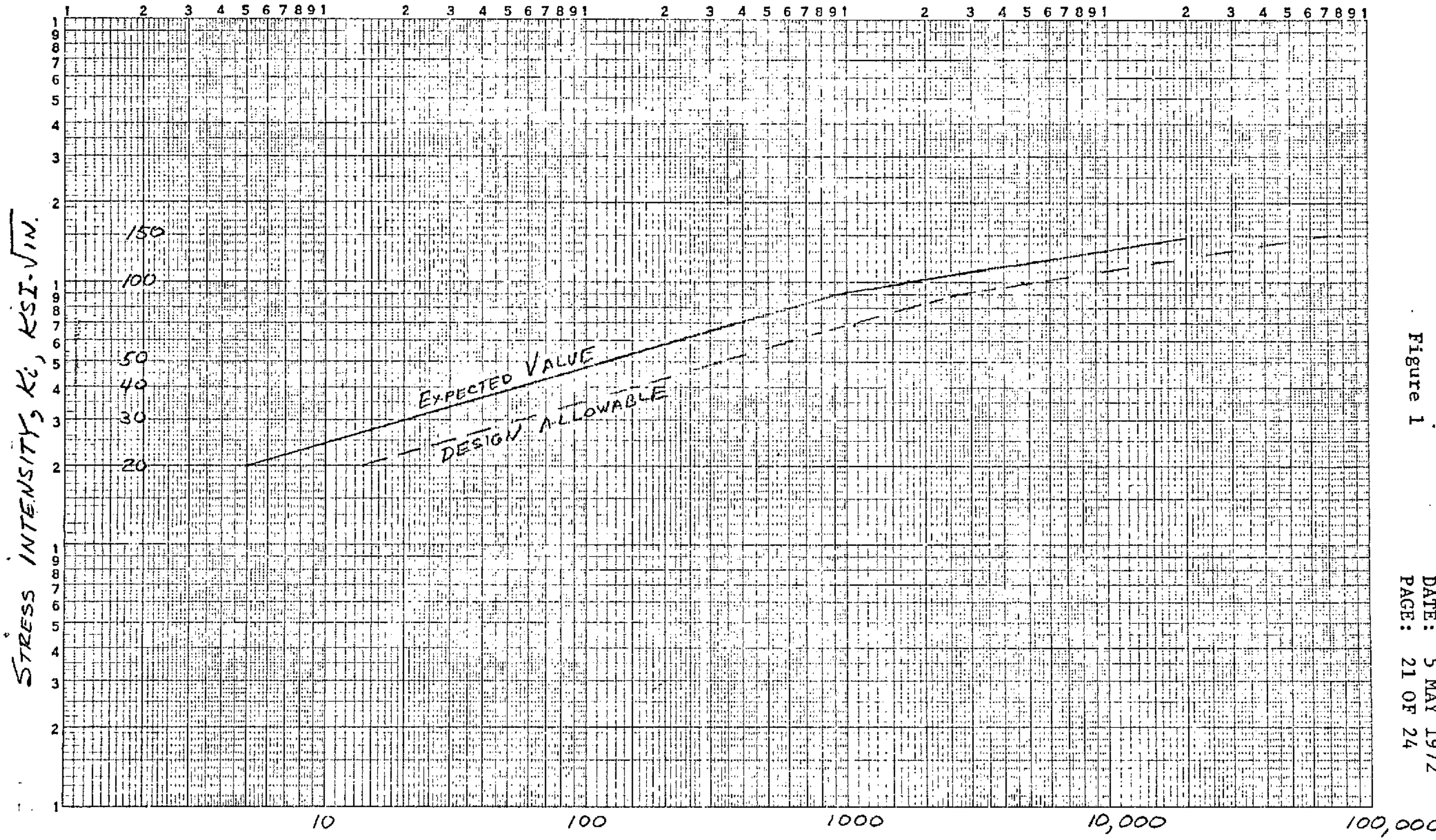

Figure 1

DRM: 04.10 R1
DATE: 5 MAY 1972
PAGE: 21 OF 24

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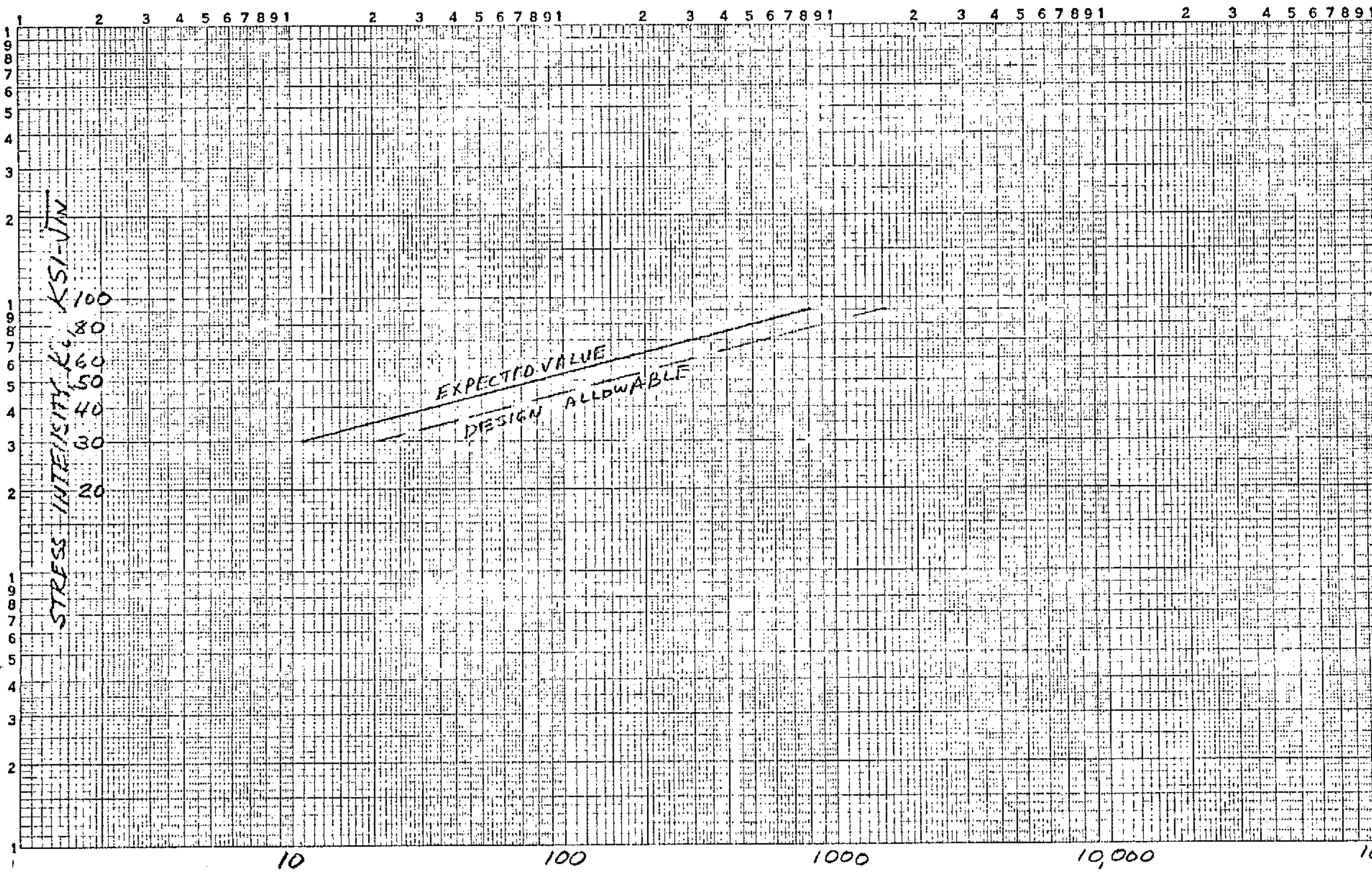
Ti 5Al 2.5Sn ELI Die Forgings   Crack Growth Rate @ -160°F (GH_2, 1200 PSIG)



CRACK GROWTH RATE, MICRO-INCHES per CYCLE

Figure 2

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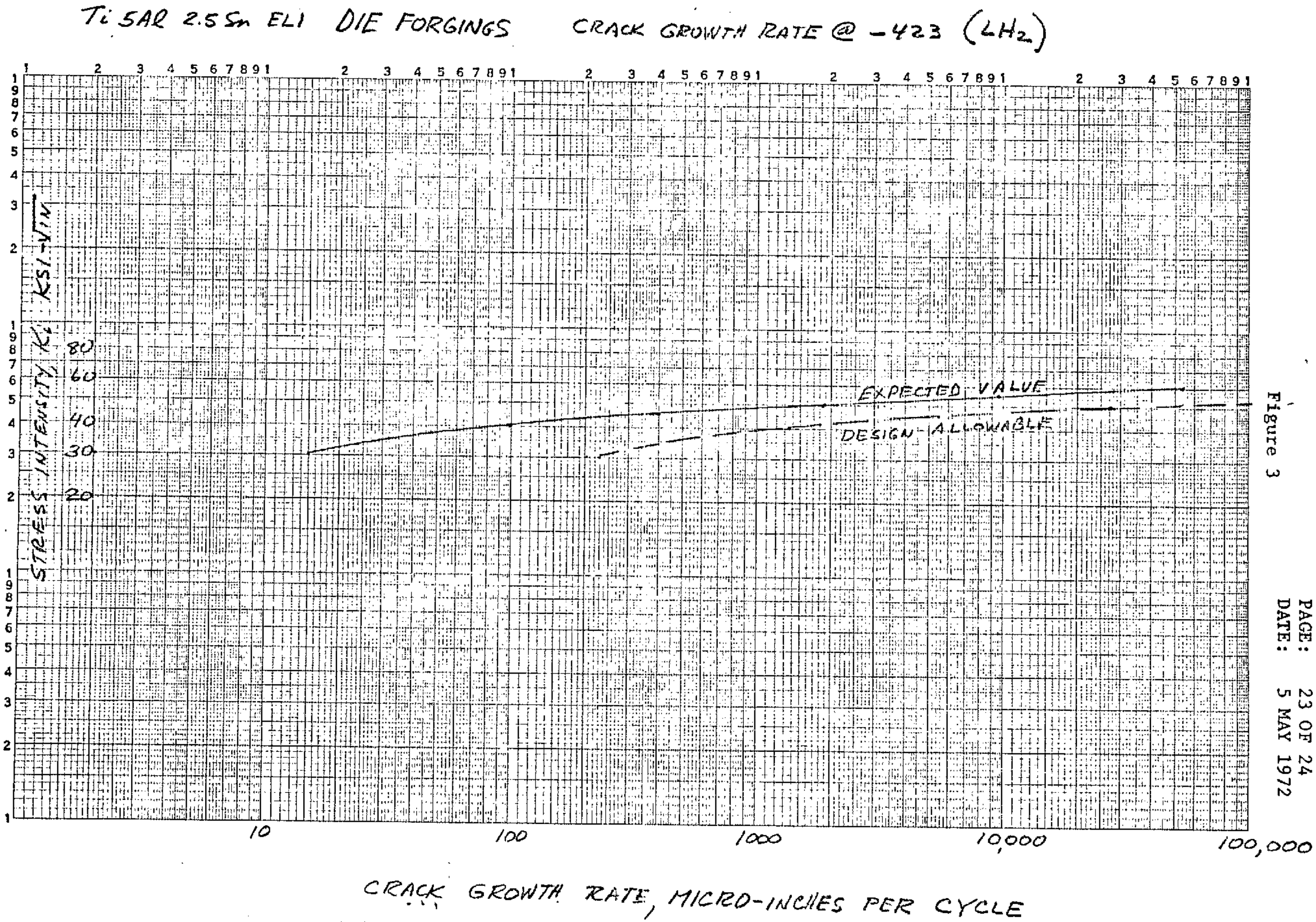
Ti 5Al 2.5Sn ELI DIE FORGINGS CRACK GROWTH RATE @ -423 (LH_2)
STRESS INTENSITY K_I KSI-$\sqrt{IN}$
80
60
40
30
20
EXPECTED VALUE
DESIGN ALLOWABLE
10
100
1000
10,000
100,000
CRACK GROWTH RATE, MICRO-INCHES PER CYCLE

Figure 3

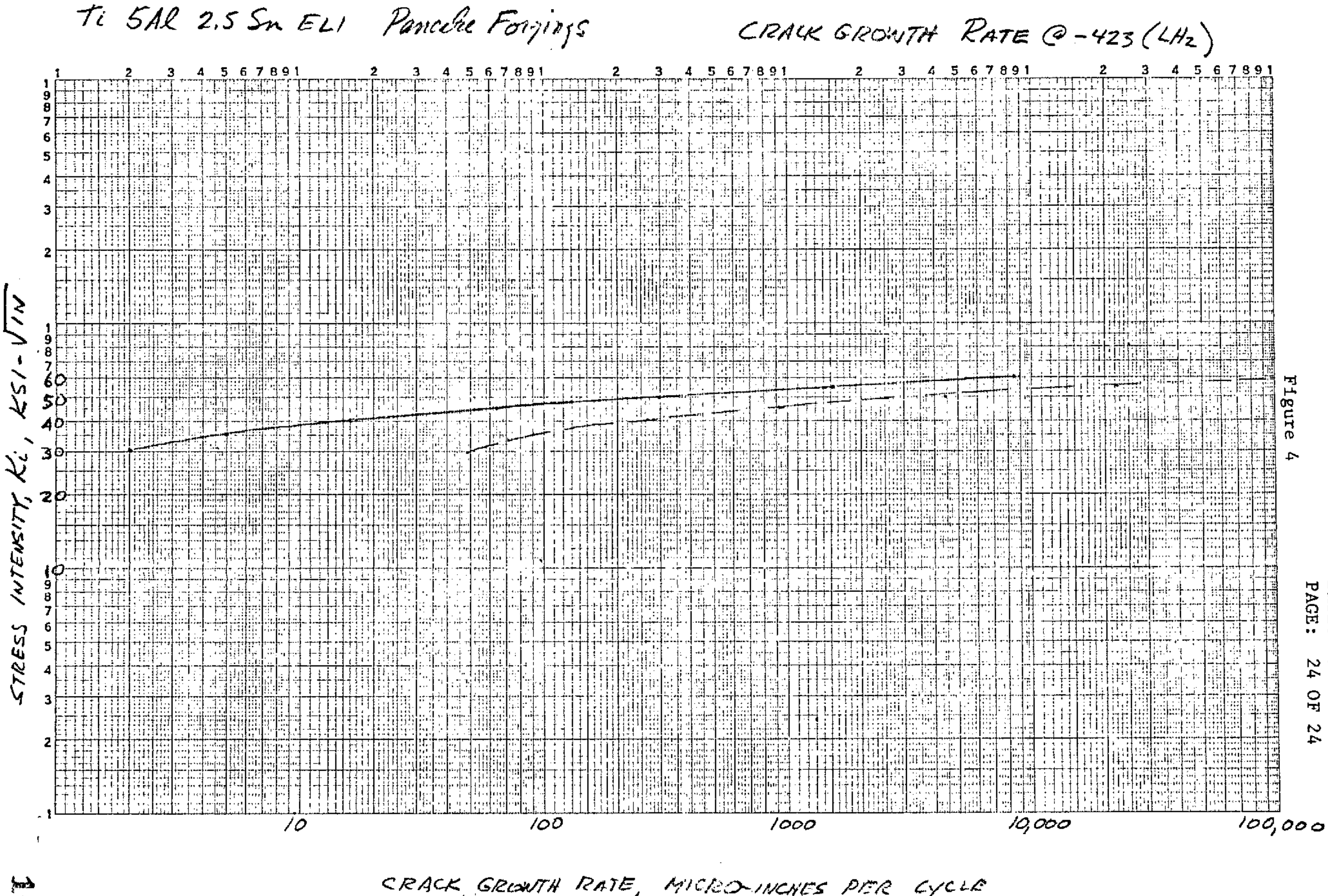

Figure 4

DRM: 04.10 R1
DATE: 5 MAY 1972
PAGE: 24 OF 24

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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EXPLANATION OF SYMBOLS ON PAGES 2 - 4

s = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

PREPARED BY: M Shaw

REVIEWED BY:

CLASSIFICATION:

UNCLASSIFIED

PER M Shaw

DATE 5/11/72

MATERIAL A-286 FORM PANCAKE FORGINGS CONDITION SOLUTION TREATED AND PRECIPITATION HARDENED

SPECIFICATIONS AMS 5737

PROPERTY CYCLES TO VARIOUS Ki LEVELS

	LOG OF CYCLES						NUMBER OF CYCLES			
Ki (KSI - IN)	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
40	4.230	.118	3	8	4.42	3.708	16980	5110	C	1
50	3.876	.118	8		4.16	3.385	7516	2427		
60	3.522	.118	9		4.14	3.033	3327	1080		
70	3.168	.118	4		4.32	2.658	1473	455		

MATERIAL A-286 FORM PANCAKE FORGINGS CONDITION SOLUTION TREATED AND PRECIPITATION HARDENED

SPECIFICATIONS AMS 5737

PROPERTY CYCLIC FRACTURE TOUGHNESS, Ki, KSI $-\sqrt{IN}$

	Ki, KSI $-\sqrt{IN}$							
NUMBER OF CYCLES	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
1	95.5	4	-	-	-	83.5 *	C	1
1000	74.8	3.17	3	8	4.42	60.8		
10000	46.5	3.67	6	8	4.22	31.0		

* CONSERVATIVE ENGINEERING ESTIMATE

MATERIAL A-286 FORM PANCAKE FORGINGS CONDITION SOLUTION TREATED AND PRECIPITATION HARDENED

SPECIFICATIONS AMS 5737

PROPERTY CRACK GROWTH RATE, da/dN, MICRO-INCHES/CYCLE

Ki (KSI - $\sqrt{IN}$)	LOG (da/dN) MEAN	s	n_e	f	k	99/95 UPPER LIMIT	da/dN 50% POINT	da/dN DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
40	0.611	.203	5	30	3.37	1.295	4	20	C	1
50	1.082	.203	13	30	3.15	1.721	12	53		
60	1.467	.203	30	30	3.05	2.086	29	122		
70	1.793	.203	24	30	3.07	2.416	62	261		
80	2.105	.332	5	15	3.68	3.327	127	2122		
90	2.736	.332	15	15	3.47	3.888	544	7728		
100	3.300	.332	11	15	3.51	4.465	1998	29196		
110	3.811	.332	5	15	3.68	5.033	6475	107835		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington, under ANSC P.O. N-01499.

One lot of A-286 Pancake Forging per AMS 5737, procured from the Whittaker Corporation, West Coast Forge Division, Compton, California was used in the test program. Fracture toughness specimens were fabricated so as to maintain the flaw propagation direction of the specimens parallel to the radial direction of the forging. A total of 11 specimens were fabricated. Testing was conducted at room temperature.

A total of 6 specimens were tested in GH_2 and 5 specimens were tested in GHe to note the effect of hydrogen on the toughness of the material. Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. The test matrix, giving the test conditions and number of specimens tested was as follows:

Test Type	Test Environment (1200 psig) GHe	GH_2
Static Fracture	1	1
Cyclic Fracture	4	5

From these results, a Ki versus number of cycles to failure curve was developed for each test condition. In addition , instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test.

The test results were as follows:

Specimen Number	Test Environment	No. of Cycles	Ki KSI - $\sqrt{IN}$
880051	GHe	1	95.1
880052	GH_2	1	95.9
880060	GHe	1042	75.7
880058	GHe	3421	62.4
880054	GHe	24800	40.3
880053	GHe	14827	37.8
880053	GHe	4800	57.6
880061	GH_2	1052	72.6
880057	GH_2	2914	62.5
880062	GH_2	2150	60.6
880056	GH_2	17176	42.8
880055	GH_2	5837	48.2

As seen from this table, one of the specimens (880053) generated two observations. In addition, instantaneous crack growth data were supplied by Boeing on computer printouts, up to 9 pairs of observations (da/dN vs Ki) per specimen.

2. DATA ANALYSIS

a. Fracture Toughness

The two static fracture toughness tests failed to yield valid K_{IC} data. Instead they are reported as a special case of Ki, at one cycle. There was no appreciable difference between the tests in helium and hydrogen; therefore the two were combined.

Regression analysis, with the aid of the G.E. computer program MULFIT was used for the cyclic fracture toughness data. An attempt was made to use the static test results in the same regression equation, but no simple function was found which would fit the combined data without a large increase in the standard error of estimate. The one cycle data reported on Page 3 merely represent the average of the 2 static tests. The standard deviation of 4 is a conservative estimate from other materials, and the design allowable shown is an engineering estimate (3-sigma) rather than a 99/95 limit.

A linear equation (Ki vs log cycles) was found to fit the combined hydrogen and the helium data very well. The results were as follows:

n	Regression Equation	s_e*	R^2
14	$\log N = 5.646 - .03539\ Ki$	.118	.934

* in logarithmic units.

This equation was used to calculate expected values of log N for various Ki levels from 40 to 70 KSI - $\sqrt{IN}$. The 99/95 lower limits were calculated in the usual manner and finally both expected values and limits were converted to anti-log units (number of cycles). To place the data in a more useful form, the equation was back-solved to yield expected and allowable Ki's for 1000 and 10000 cycles. These are given on Page 3. Results are shown graphically in Figure 1.

b. Crack Growth Rate (da/dN)

The data from the computer printouts were divided into two groups, below and above Ki = 80. These represent the two slopes of the lines relating log (da/dN) as a function of Ki. The computer program MULFIT was used to determine the least squares regression lines. The analysis was first done separately for the hydrogen and helium groups, but when no appreciable difference was found they were combined.

The results were:

	n	Regression Equation*	s_e**	R^2
Ki $\leq$ 80	32	log y = -7.183 + 4.865 log x	.203	.804
Ki > 80	17	log y = 21.379 + 12.340 log x	.332	.755

* y = da/dN, micro-inches per cycle; x = Ki

** in logarithmic units.

These equations were used to calculate expected values of log (da/dN) for various Ki levels. Design allowables were then calculated in the usual manner. The results are plotted in Figure 2.

3. REFERENCES

(1) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

EUGENE DIETZGEN CO.
MADE IN U. S. A.

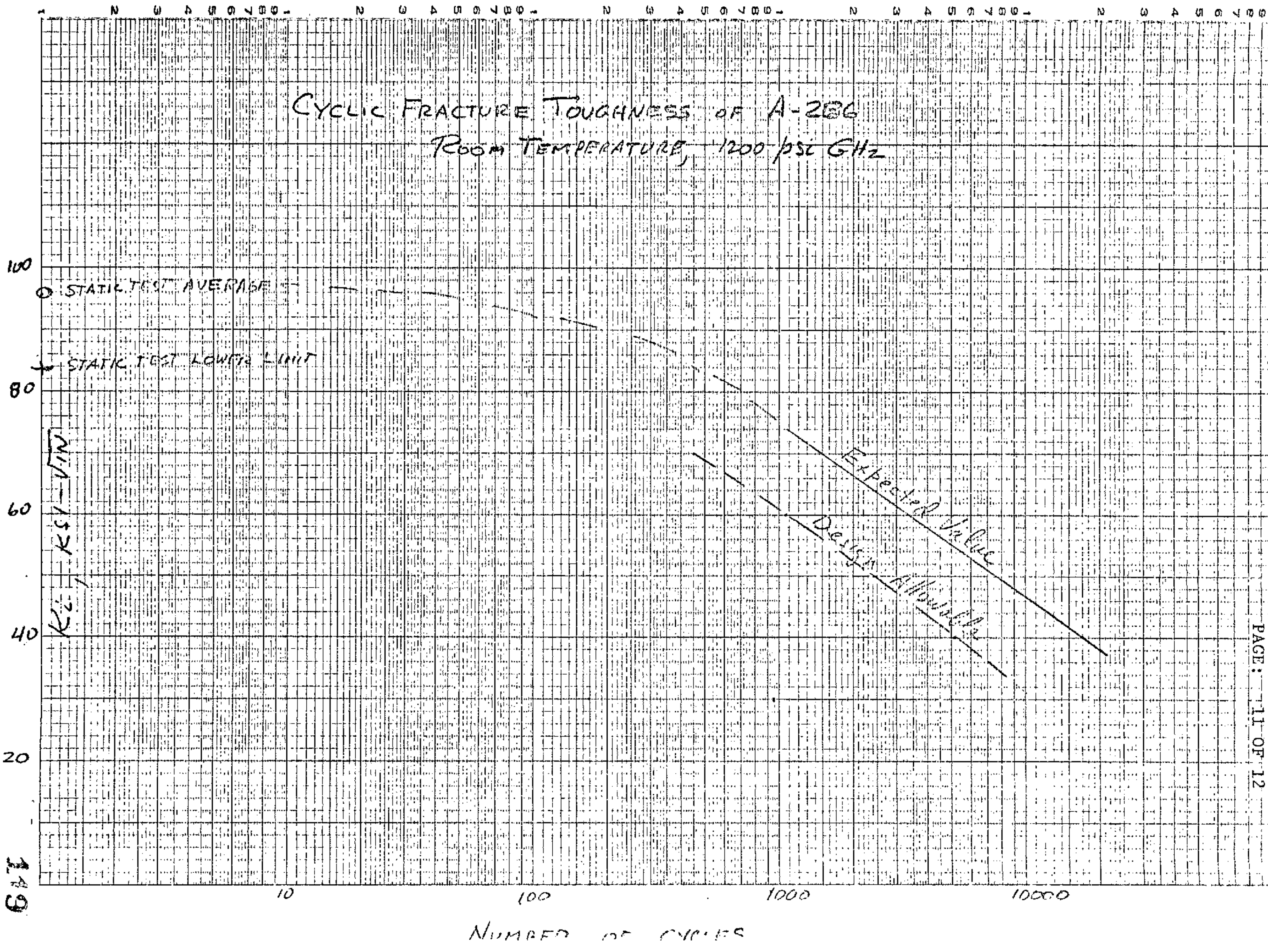


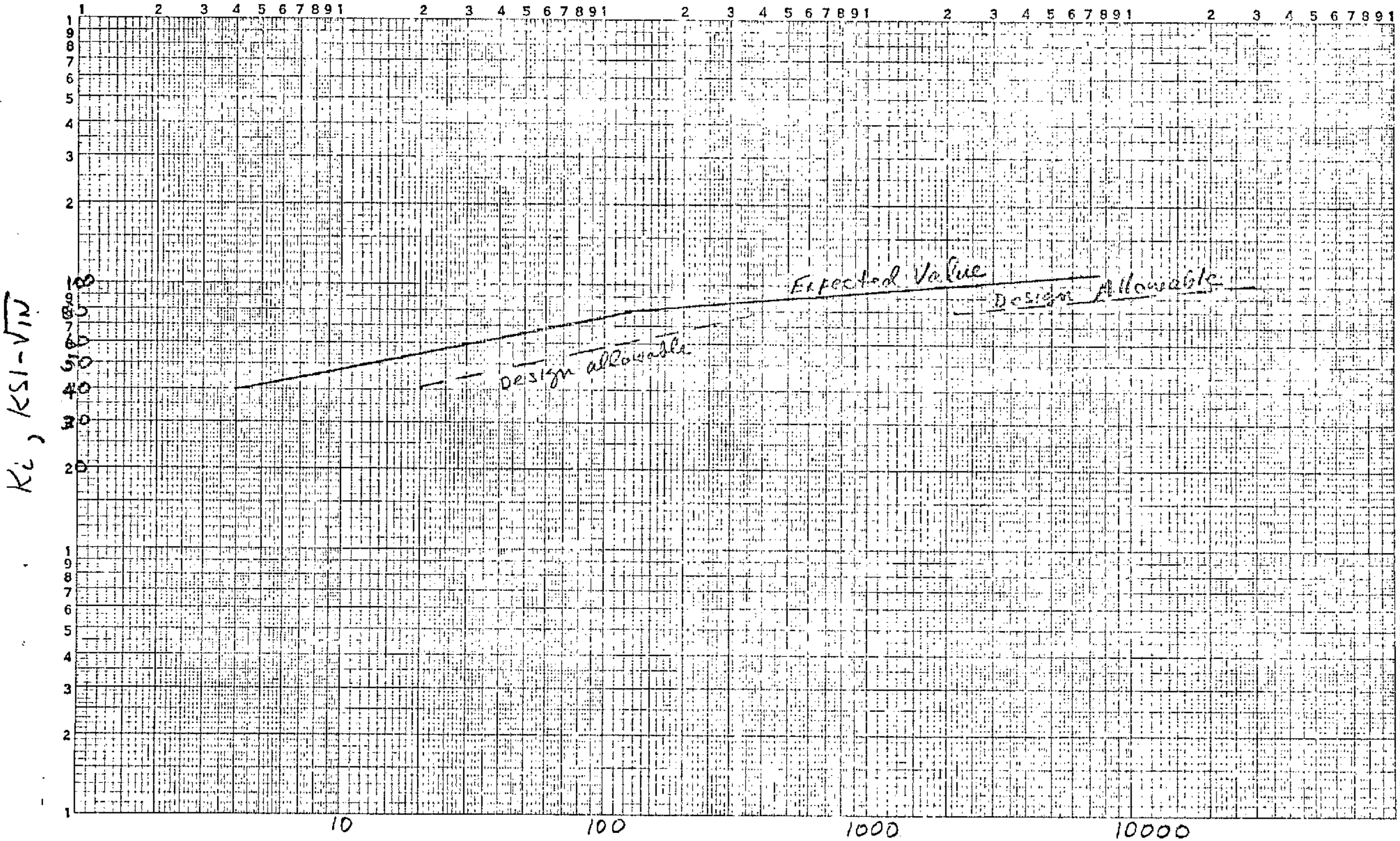
Figure 1

DRM: 05.07
DATE: 12 MAY 1972
PAGE: 11 OF 12

NO. 340-L35 DIETZGEN GRAPH PAPER
LOGARITHMIC
3 CYCLES X 5 CYCLES

EUGENE DIETZGEN CO.
MADE IN U. S. A.

CRACK GROWTH RATE OF A286, ROOM TEMP, 1200 PSI GH_2



CRACK GROWTH RATE, MICRO-INCHES PER CYCLE

Figure 2

DRM: 05.07
DATE: 12 MAY 1972
PAGE: 11 OF 11

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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EXPLANATION OF SYMBOLS ON PAGES 2 AND 3:

s_e = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s_e

NOTE: THIS REVISION SUPERSEDES DRM 07.04 DATED 20 JANUARY 1971. IT IS BASED ON OFFICIAL DATA (REF. 2), INSTEAD OF PRELIMINARY DATA (REF. 1). THE DATA HAVE BEEN COMPLETELY RE-ANALYZED, AND A NEW REGRESSION MODEL, BOTH SIMPLER AND BETTER FITTING, WAS SELECTED. THE TEXT HAS BEEN RE-WRITTEN AND AN S-N CURVE HAS BEEN INCLUDED.

PREPARED BY M Shey

REVIEWED BY:

CLASSIFICATION:

UNCLASSIFIED

PER M Shey

DATE 3-3-72

MATERIAL AA 6061 FORM SHEET (.160") CONDITION T 6

SPECIFICATIONS DIRECTION TRANSVERSE

PROPERTY FLEXURAL FATIGUE CYCLE LIFE @ RT

	LOG OF CYCLES				NUMBER OF CYCLES X 10^3					
STRESS, KSI	MEAN	s_e	k	99/95 LIMIT	50% POINT	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
32	4.683	.131	3.12	4.274	48	19	9	41	C	2
30	4.826		3.06	4.425	67	27	12			
28	4.991		3.00	4.598	98	40	18			
26	5.180		2.95	4.794	151	62	27			
24	5.401		2.92	5.018	252	104	38			
22	5.662		2.92	5.279	459	190	42			
20	5.975		2.93	5.591	944	390	36			
18	6.358		2.96	5.970	2280	934	25			
16	6.837		3.01	6.443	6871	2771	17			

MATERIAL AA 6061 FORM SHEET (.160") CONDITION T 6

SPECIFICATIONS ____ DIRECTION TRANSVERSE

PROPERTY FLEXURAL FATIGUE STRENGTH @ RT

NO. OF CYCLES	LOG OF CYCLES	RECIPROCAL STRESS MEAN	s	k	99/95 LIMIT	STRESS, KSI MEAN	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
10^5	5.0	.0358	.00190	3.00	.0415	27.9	24.1	18	41	C	2
3.16×10^5	5.5	.0431		2.93	.0487	23.2	20.5	40	41		
10^6	6.0	.0503		2.93	.0559	19.9	17.9	36	41		
3.16×10^5	6.5	.0576		2.98	.0633	17.4	15.8	22	41		

I. TEST DESCRIPTION

Flexural fatigue tests were conducted at room temperature on 50 specimens of AA 6061=T6 .160-in. sheet from Harvey Aluminum Heat No. 333/6402-A. The testing was performed by Boeing Wichita per ANSC Purchase Order N-00235, as described in References (1) and (2). Specimens were oriented so that flexing occurred perpendicular to the longitudinal grain flow direction. Testing was conducted at a number of stress levels, from 15 to 38.5 ksi, selected to produce failure at between 10^4 and 10^7 cycles. The following data were obtained:

STRESS LEVEL KSI

15	16	18	20	22	24	28	31	38.5
10000+	6056	2008	1189	380	361	117	49.6	12.3
	10000+	2690	976	414	261	84	42.0	11.6*
	6405	1788	798	671	397	139		26.8*
	9332	2516	1150	367	251	95		15.9*
	11932	1720	690	351	187	127		
	3490	3826	527	598	295	132		
	3517*	1659	1703*		367	83		
	5125*	2000*	1236*					
	1633*	1906*						
	7572*							
	1480*							

\+ DID NOT FAIL. Observation used in analysis by assuming failure at cycle life shown.

* NOT USED IN ANALYSIS. Test considered invalid, usually because failure occurred at a grip.

II. DATA ANALYSIS

After the indicated exclusions, 43 observations remained. The data were analyzed by regression analysis following the general methodology of Reference (3). The computer program MULFIT on the G.E. Time-Sharing Computer System was used to select a regression model for log cycle life versus stress and to obtain the associated least squares regression equation. The results of this analysis were:

n	Regression Equation *	Standard Error of Estimate (log units)	Index of Determination
43	$\log y = 2.529 + 68.924\ (1/x)$	0.131	.965

* y = number of cycles to failure

x = stress level, ksi

The reciprocal transform of stress used in the above equation, exhibited a better fit to the data than either the linear or logarithmic transforms.

The predicted mean values of log y and the effective sample sizes (n_e) were calculated for a number of different stress levels as shown on Page 2. One-sided 99/95 tolerance limit factors (k) corresponding to the effective sample sizes were determined by means of the computer program TFAC. The 99/95 lower limits were then calculated at each stress level in log units. Finally, both the means and 99/95 limits were converted back to numbers of cycles by taking their anti-logs. S-N curves are shown in Figure 1.

On Page 3, the predicted strength for various number of cycles to failure, and the associated n_e, k, and design allowables are shown. The method used to estimate the distribution of strength from the distribution of cycles to failure was an approximate one.

The 99/95 limits were first calculated in reciprocal stress units. Finally, the means and 99/95 limits were converted back to KSI.

The data are categorized as "C" because only one material lot was used.

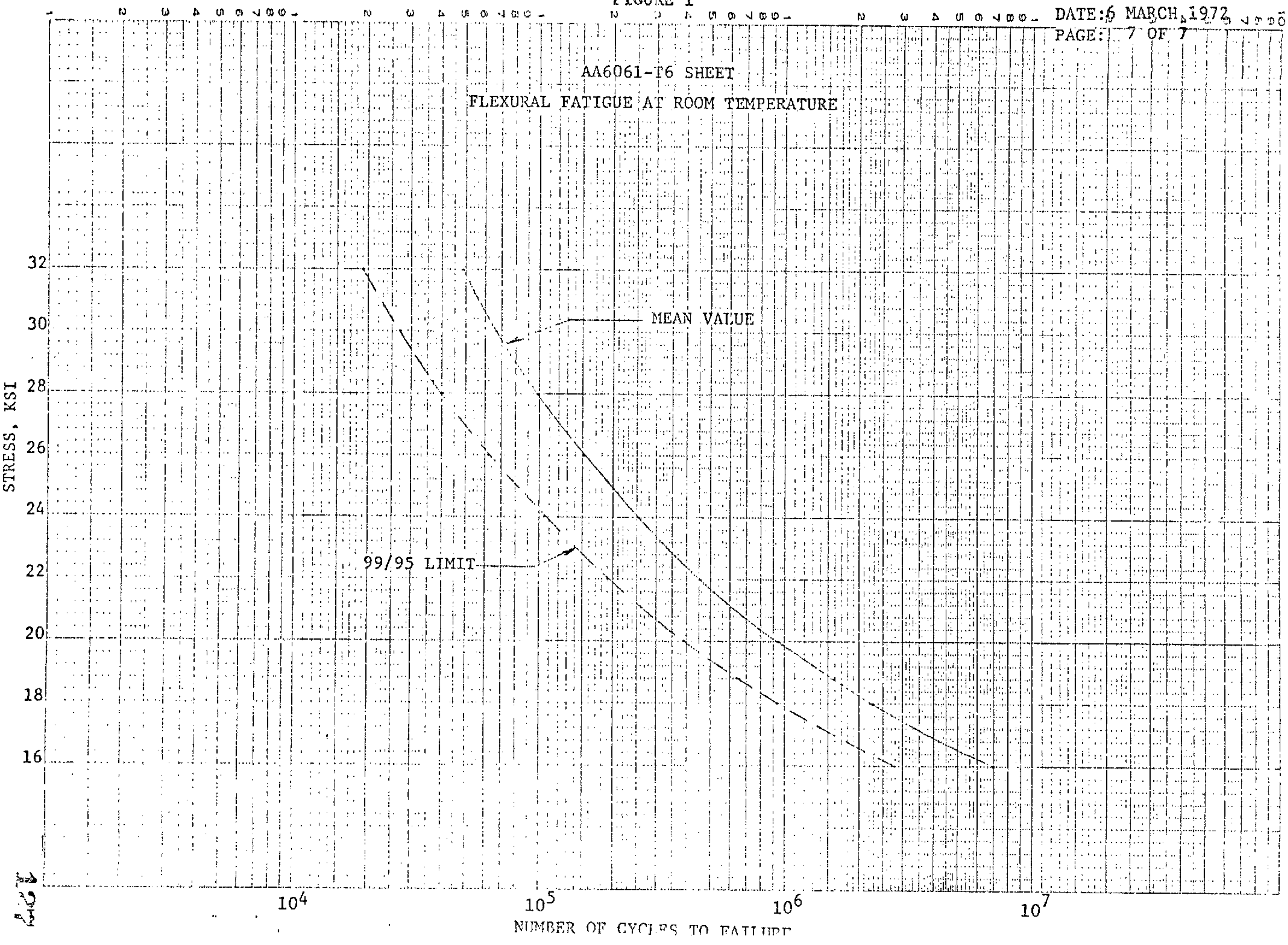
III. REFERENCES

(1) First Quarterly Report, CY 1971, NERVA Materials Development, s131-MQR06-W187f2.

(2) Boeing, Wichita Division, Report No. 1433, "Aerojet-General Flexure Fatigue Test Program - 6061 T6 Aluminum Alloy", 9 December, 1970.

(3) NERVA Program Procedure R101-NRP02, "Sampling for Fatigue Test".

FIGURE 1


AA6061-T6 SHEET
FLEXURAL FATIGUE AT ROOM TEMPERATURE
MEAN VALUE
99/95 LIMIT
STRESS, KSI
32
30
28
26
24
22
20
18
16
10^4
10^5
10^6
10^7
NUMBER OF CYCLES TO FAILURE

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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PREPARED BY: M Shev

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 3/6/72

MATERIAL SS 301 FORM SHEET (.035") CONDITION FULL HARD

SPECIFICATIONS QQS-766C

PROPERTY ULTIMATE TENSILE STRENGTH, KSI

GASEOUS ENVIRONMENT	NO. OF OBSERVATIONS	MEAN VALUE $\bar{X}$	ESTIMATED STANDARD DEVIATION s	ESTIMATED * DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
HYDROGEN @ RT	3	69	10	39	C	1
INERT @ RT	1	220	10	190	C	1

* CONSERVATIVE ENGINEERING ESTIMATE, NOT 99/95 LIMIT

I. TEST DESCRIPTION

Four specimens of 301 stainless steel were tensile-tested at room temperature, three in gaseous hydrogen @ 1200 psi and one in gaseous helium at the same pressure. The work was performed by the ALRC Research Physics Laboratory and is reported in Reference (1).

The material, from Ulbrich Heat No. 39497 was .035" sheet in the full hard condition, per Specification QQS-766C. The specimens were flat, dumbbell shaped, and about 0.25" in width. The test results (ultimate tensile strength, ksi) were:

Helium	Hydrogen
220	59
	73
	74

II. DATA ANALYSIS

The material obviously underwent severe embrittlement in hydrogen. There are too few observations to warrant much statistical analysis. To obtain an estimate of the specimen-to-specimen variability in the hydrogen group, the standard deviation of the above group was pooled with that of a group of four AISI 9310 specimens, also tested in hydrogen at room temperature and reported in References (1) and (2). The resulting estimated standard deviation was 10 ksi. A 99/95 design allowable calculated in the usual manner would be extremely low and therefore unusable. Since the data are "C" category, a conservative engineering estimate in lieu of a 99/95 limit is considered adequate and was made by subtracting 3 standard deviations from the mean.

A standard deviation of 10 ksi was also used for the group tested in helium. This is certainly conservative because the variability observed for the other materials of Reference (1) is much lower. The estimated design allowable is also a 3-sigma lower limit.

III. REFERENCES

(1) "NERVA Tensile Test Report", Research Physics Laboratory, ALRC, 26 July 1971.

(2) ANSC DRM 31.02, dated 10 September 1971. (Ultimate Tensile Strength of AISI 9310).

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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SYMBOLS USED ON PAGES 2 - 4

$\bar{X}$ = GROUP AVERAGES

n = SAMPLE SIZE ASSOCIATED WITH $\bar{X}$

f = DEGREES OF FREEDOM FOR POOLED WITHIN-GROUP STANDARD DEVIATION

k = 99/95 LOWER TOLERANCE LIMIT FACTOR FOR n AND f

s = POOLED WITHIN-GROUP STANDARD DEVIATION

PREPARED BY: M J Davidson

REVIEWED BY: M Slev

CLASSIFICATION:

UNCLASSIFIED

PER M J Davidson

DATE 20 March 1972

MATERIAL HASTELLOY X FORM PLATE CONDITION FURNACE BRAZED

SPECIFICATIONS AGC 90056 D

PROPERTY TENSILE ULTIMATE STRENGTH, KSI, @ 540°R

FLUENCE, N/CM^2 ($E > 1.0$ MeV)	$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED	135.2	2.01	4	19	3.621	127.9	C	(1)
5.4×10^{17}	142.1	2.01	4	19	3.621	134.8	C	(1)
1.2×10^{18}	150.7	2.01	4	19	3.621	143.4	C	(1)
5.0×10^{18}	170.5	2.01	3	19	3.686	163.1	C	(1)
5.0×10^{18} + 540°R ANNEAL *	162.2	2.01	9	19	3.408	156.0	C	(1)

* 10, 100 AND 1000 MINUTES. NO SIGNIFICANT EFFECT OF ANNEALING TIMES; THEREFORE DATA POOLED.

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

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MATERIAL HASTELLOY X FORM PLATE CONDITION FURNACE BRAZED

SPECIFICATIONS AGC 90056 D

PROPERTY TENSILE YIELD STRENGTH, KSI @ 140°R

FLUENCE, N/CM^2 (E > 1.0 MeV)	$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED	71.2	1.77	4	19	3.621	64.8	C	(1)
5.4×10^{17}	101.6	1.77	4	19	3.621	95.2	C	(1)
1.2×10^{18}	113.8	1.77	4	19	3.621	107.4	C	(1)
5.0×10^{18}	144.8	1.77	3	19	3.686	138.3	C	(1)
5.0×10^{18} + 540°R ANNEAL *	126.2	1.77	9	19	3.408	120.2	C	(1)

* 10, 100 AND 1000 MINUTES. NO SIGNIFICANT EFFECT OF ANNEALING TIMES; THEREFORE DATA POOLED

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

MATERIAL HASTELLOY X FORM PLATE CONDITION FURNACE BRAZED

SPECIFICATIONS AGC 90056 D

PROPERTY ELONGATION, % @ 140°R

FLUENCE, N/CM^2 ($E > 1.0$ MeV)	$\bar{X}$	s	n	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
UNIRRADIATED	28.0	1.31	4	19	3.621	23.3	C	(1)
5.4×10^{17}	20.3	1.31	4	19	3.621	15.6	C	(1)
1.2×10^{18}	19.0	1.31	4	19	3.621	14.3	C	(1)
5.0×10^{18}	14.0	1.31	3	19	3.686	9.2	C	(1)
5.0×10^{18} + 540°R ANNEAL *	16.6	1.31	9	19	3.408	12.1	C	(1)

* 10, 100 AND 1000 MINUTES. NO SIGNIFICANT EFFECT OF ANNEALING TIMES; THEREFORE DATA POOLED.

NOTE: FOR MATERIAL EVALUATION ONLY. DO NOT USE FOR DESIGN.

I. TEST DESCRIPTION (REFERENCE [1])

Round button-head tensile specimens per AGC P/N 1134298 were prepared from a Hastelloy X plate from Union Carbide Heat 2610-6-2183. It was previously used as part of a coolant channel and subjected to furnace braze cycles 1950, 1825 and 1775°F.

The specimens were irradiated at 140°R to three different fluence levels in test GTR-20C at Convair Aerospace Division/Fort Worth. In addition, three groups of specimens were annealed at 10, 100 and 1000 minutes at 540°R after irradiation to the highest of the three fluence levels. The irradiated specimens and an unirradiated control group were tensile tested at 140°R. The results of the tensile tests are shown in the following table where each entry is the average of 3 or 4 specimens.

Fluence (n/cm^2, E > 1 MeV)	Post-Irradiation Anneal, 540°R (Minutes)	No. of Specimens	Ultimate Strength (ksi)	Yield Strength (ksi)	Elongation (%)
Unirradiated	0	4	135.2	71.2	28.0
5.4×10^{17}	0	4	142.1	101.6	20.3
1.2×10^{18}	0	4	150.7	113.8	19.0
5.0×10^{18}	0	3	170.5	144.8	14.0
5.0×10^{18}	10	3	162.3	127.8	16.7
5.0×10^{18}	100	3	162.9	126.6	15.3
5.0×10^{18}	1000	3	161.7	124.4	17.8

II. DATA ANALYSIS

For all three properties, the within-group variances were found to be homogeneous and accordingly were pooled over the seven groups. The resulting pooled standard deviations were used to calculate the 99/95 lower limits. There was no significant difference between specimens annealed for 10, 100 or 1000 minutes, therefore, the data from these three groups were pooled for each property for calculation of mean and degrees of freedom. Yield and ultimate strengths increased with increasing fluence and elongation decreased. Original properties were partially recovered in the 540°R post irradiation anneal.

III. REFERENCES

1. General Dynamics, Convair Aerospace Division Report FZK-381, NERVA Irradiation Program, GTR-20C, Combined Effects of Reactor Radiation and Cryogenic Temperature on NERVA Structural Materials, May 1971.

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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PREPARED BY: M Shev

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER: M Shev

DATE: 3/21/72

MATERIAL HASTELLOY X FORM ALL CONDITION ALL

SPECIFICATIONS

PROPERTY DYNAMIC MODULUS, PSI (X 10^6)

TEMPERATURE °F	NO. OF OBSERVATIONS	MEAN VALUE $\bar{X}$	STANDARD DEVIATION s	DEGREES OF FREEDOM f	TOLERANCE LIMIT FACTOR k	DESIGN ALLOWABLES LOWER	DESIGN ALLOWABLES UPPER	DATA CATEGORY	SOURCE REFERENCE
-320	4	32.74	0.64	9	4.68	29.7	35.7	C	1
RT	4	31.29	0.64	9	4.68	28.3	34.3	C	1
600	4	29.01	0.64	9	4.68	26.0	32.0	C	1

MATERIAL HASTELLOY X FORM ALL CONDITION ALL

SPECIFICATIONS

PROPERTY POISSON'S RATIO

TEMPERATURE °F	NO. OF OBSERVATIONS	MEAN VALUE $\bar{X}$	STANDARD DEVIATION s	DEGREES OF FREEDOM f	TOLERANCE LIMIT FACTOR k	DESIGN ALLOWABLES LOWER	DESIGN ALLOWABLES UPPER	DATA CATEGORY	SOURCE REFERENCE
-320	4	.2935	.0031	9	4.68	.279	.308	C	1
RT	4	.2968	.0031	9	4.68	.282	.311	C	1
600	4	.3058	.0031	9	4.68	.291	.320	C	1

I. TEST DESCRIPTION

Dynamic Modulus and Poisson's ratio of Hastelloy-X at -320°F, RT, and 600°F were measured by WANL per ANSC P. O. N-01728. The material submitted for testing was 5 1/4" X 1 1/4" plate per AGC 90057-20, in the simulated furnace-brazed condition.

A single test specimen, per ANSC P/N 1138310, was fabricated from the material and used for all the determinations. An ultrasonic technique, described in Reference (1), was used. Four determinations were made at each of the three temperatures. The results are reported in Reference (2) and are considered to apply for all forms and conditions of the material. Averages for each temperature are shown on pages 2 and 3.

II. DATA ANALYSIS

Normally, design values for these physical properties would be reported as nominal $\pm$ 5%. (Reference (3)). However, since the replicate determinations provide a measure of experimental error variability, the design values were calculated as true 99/95 limits. All variability is attributed to test error rather than to the material.

The within-temperature variances were found to be homogeneous by means of the Bartlett-Box test and accordingly were pooled into a single variance estimate, s^2, based on 9 degrees of freedom. Two-sided tolerance limit factors, k, were determined from Reference (4). Finally, 99/95 limits were calculated as $\overline{X} \pm ks$.

III. REFERENCES

1. WANL Test Plan 38-10, Project 485G, dated 5 August 1971.

2. Letter from R. F. Dickson (WANL) to J. L. Dooling (ANSC) dated 22 October 1971, Subject: "Project 485, Test Plan M-38 Line 10, Requisition No. N-01728: Dynamic Modulus Tests.

3. Letter, L. C. Corrington (SNSO-C) to W. O. Wetmore (ANSC) dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data".

4. A. Weissberg and G. H. Beatty, "Tables of Tolerance - Limit Factors for Normal Distributions", Technometrics, Vol. 2, No. 4 p. 483-500 (1960).

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EXPLANATION OF SYMBOLS ON PAGES 2 - 4

s = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s

PREPARED BY: M Shew

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Shew

DATE 5/11/72

MATERIAL HASTELLOY "X" FORM PLATE CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS AGC 90057-2D

PROPERTY NUMBER OF CYCLES TO VARIOUS Ki LEVELS

	LOG OF CYCLES						NUMBER OF CYCLES			
Ki KSI - $\sqrt{IN}$	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
30	4.444	.0464	2	10	4.35	4.242	27789	17465	C	1
40	3.852		3		4.17	3.659	7108	4555		
50	3.310		4		4.07	3.121	2041	1322		
60	2.818		6		3.96	2.634	658	431		
70	2.376		6		3.96	2.192	238	156		
80	1.984		5		4.00	1.798	97	63		
90	1.643		3		4.17	1.450	44	28		

MATERIAL HASTELLOY "X" FORM PLATE CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS AGC 90057-2D

PROPERTY CYCLIC FRACTURE TOUGHNESS, Ki, KSI - $\sqrt{IN}$

	Ki, KSI - $\sqrt{in}$							
NO. OF CYCLES	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	DATA CATEGORY	SOURCE REFERENCE
1	97.0	4 *	-	-	-	85.0*	C	1
100	79.6	1.25	5	10	4.00	74.6		
1000	56.2	0.96	6	10	3.96	52.4		
10000	37.4	0.78	2	10	4.35	34.0		

* CONSERVATIVE ENGINEERING ESTIMATE; NOT 99/95 LIMIT.

MATERIAL HASTELLOY "X" FORM PLATE CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS AGC 90057-2D

PROPERTY CRACK GROWTH RATE (da/dN), MICRO-INCHES PER CYCLE

	LOG (CRACK GROWTH RATE)						CRACK GROWTH RATE			
Ki KSI - $\sqrt{IN}$	MEAN	s	n_e	f	k	99/95 UPPER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
40	1.167	.177	5	35	3.33	1.756	15	57	C	1
50	1.698		11		3.13	2.252	50	179		
60	2.131		21		3.03	2.667	135	465		
70	2.498		34		2.99	3.027	315	1065		
80	2.815		35		2.98	3.342	654	2200		
90	3.095		25		3.01	3.628	1246	4244		
100	3.346		17		3.06	3,888	2218	7720		
110	3.573		12		3.11	4.123	3738	13288		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington, under ANSC P. O. N-01499.

One lot of Hastelloy "X" plate per AGC 90057-2D, Heat No. 2610-0-4007, procured from the Stellite Division of the Cabot Corporation, Kokomo, Indiana, was used in this test program. The material was subjected to a final heat treat (simulated furnace braze cycle) by Pyromet. Fracture toughness specimens were fabricated from the plate material so as to maintain the flaw propagation direction of the specimens parallel to the rolling direction. A total of 12 specimens were fabricated. Testing was conducted at room temperature.

A total of 6 specimens were tested in GH_2 and 6 specimens were tested in GHe to note the effect of hydrogen on the toughness of the material. Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. The test matrix, giving the test conditions and number of specimens tested was as follows:

Test	Test Environment (1200 psig)	
Type	GHe	GH_2
Static Fracture	1	1
Cyclic Fracture	5	5

From these results, a Ki versus number of cycles to failure curve was developed for each test condition. In addition, instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test.

The test results were as follows:

Specimen Number	Test Environment	No. of Cycles	Ki KSI - $\sqrt{IN}$
880063	GH	1	95.5
880064	GHe	1	98.6
880068	GHe	445	69.1
880065	GHe	1475	56.7
880069	GHe	8469	42.7
880072	GHe	16923	37.3
880066	GHe	51075	28.6
880066	GHe	112	57.4
880070	GH_2	214	72.7
880070	GH_2	41	92.2
880067	GH_2	1120	56.4
880067	GH_2	49	86.9
880071	GH_2	4307	43.8
880071	GH_2	115	78.7
880073	GH_2	6598	39.3
880073	GH_2	403	64.8

As seen from this table, four of the specimens generated two observations each. In addition, instantaneous crack growth data were supplied by Boeing on computer printouts, up to 11 pairs of observations (da/dN vs Ki) per specimen.

2. DATA ANALYSIS

a. Fracture Toughness

The two static fracture toughness tests failed to yield valid K_{IC} data. Instead they are reported as a special case of Ki, at one cycle. There was no appreciable difference between the tests in helium and hydrogen; therefore the two were combined.

Regression analysis, with the aid of the G.E. computer program MULFIT was used for the cyclic fracture toughness data. An attempt was made to use the static test results in the same regression equation, but no simple function was found which would fit the combined data without a large increase in the standard error of estimate. The one cycle data reported on Page 3 merely represent the average of the 2 static tests. The standard deviation of 4 is a conservative estimate from other materials, and the design allowable shown is an engineering estimate (3-sigma) rather than a 99/95 limit.

A quadratic equation (Ki vs log cycles) was found to fit the data very well. However, to provide for a moderate observed difference between test results in hydrogen and helium, an extra variable, x_2,was introduced into the regression equation and assigned the values $x_2 = 0$ for hydrogen, $x_2 = 1$ for helium. The results were as follows:

n	Regression Equation	s_e*	R^2
14	$\log N - 6.521 - .07676\ x_1 + 2.507 + 10^{-4}\ x_1^{2} + .183\ x_2$	.0464	.997

* N = number of cycles; x_1 = Ki; x_2 = test environment.

** in logarithmic units.

This equation was used to calculate expected values of log N for various Ki levels from 30 to 90 KSI $-\sqrt{\text{IN.}}$ By assigning $x_2 = 0$, the calculated values applied to the hydrogen environment, the worst case. The 99/95 lower limits were calculated in the usual manner and finally both expected values and limits were converted to anti-log units (number of cycles). To place the data in a more useful form, the equation was back-solved to yield expected and allowable Ki's for various numbers of cycles. These are given on Page 3.

b. Crack Growth Rate (da/dN)

The data from the computer printouts were divided into two groups, below and above Ki = 100. These represent the two slopes of the lines relating log (da/dN) as a function of Ki. However there were insufficient data for Ki > 100, and only one of the slopes could be determined. The computer program MULFIT was used to determine the least squares regression lines. The analysis was done separately for the hydrogen and helium groups. The tests in hydrogen showed slightly higher crack growth rates at all Ki levels; therefore the regression line for this group was the only one used to calculate expected values and design allowables.

The results were:

Regression Equation*	s_e**	R^2
$\log y = -7.606 + 5.476 \log x$	.177	.930

* y = da/dN, micro-inches per cycle; x = Ki

** in logarithmic units.

NOTE: The above regression equation applies at all levels of Ki from 40 to 110.

These equations were used to calculate expected values of log (da/dN) for various Ki levels. Design allowables were then calculated in the usual manner. The results are plotted in Figure 2.

3. REFERENCES

(1) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

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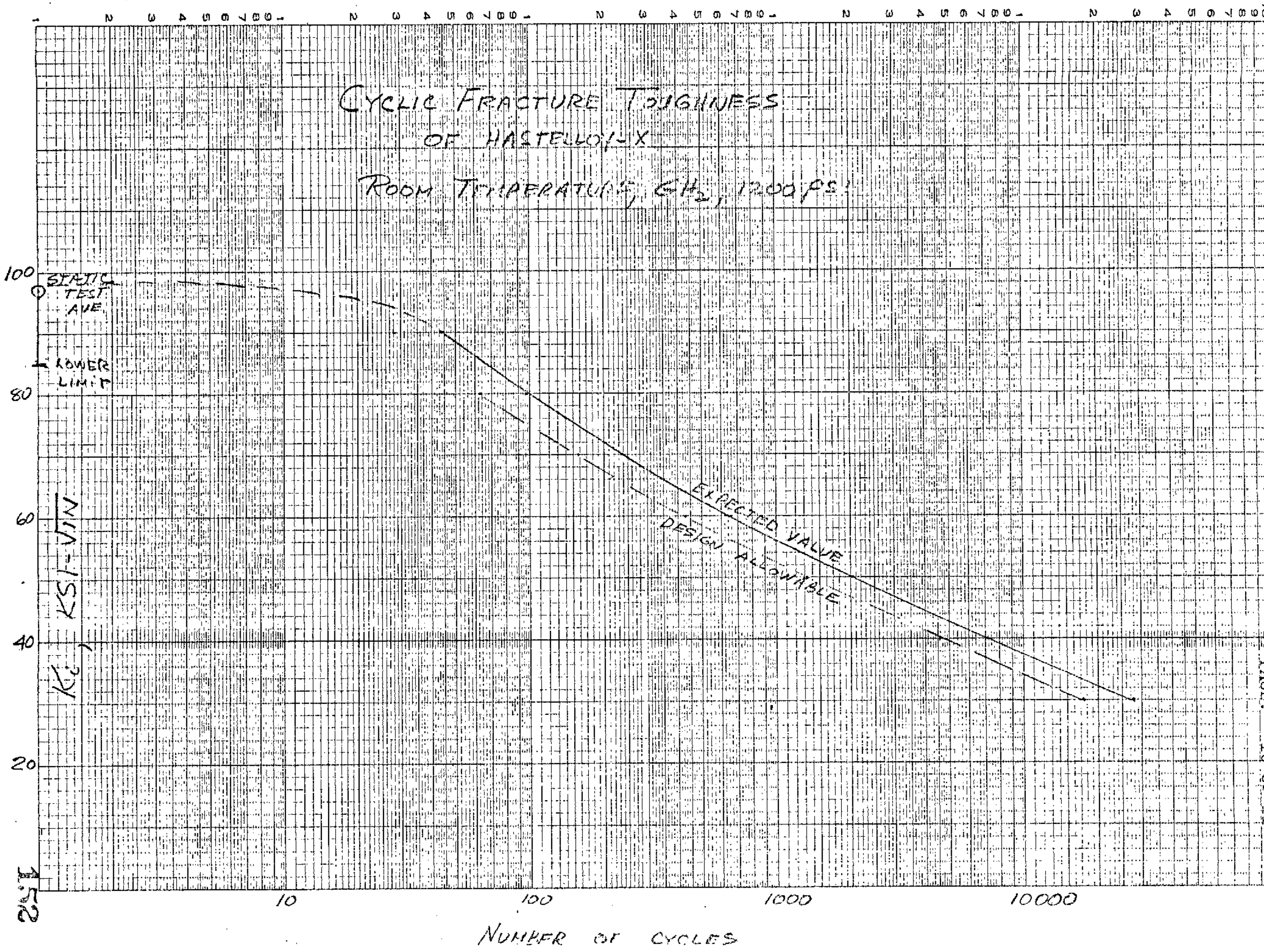

Figure 1

DRM: 12.03
DATE: 11 MAY 1972
PAGE: 10 OF 11

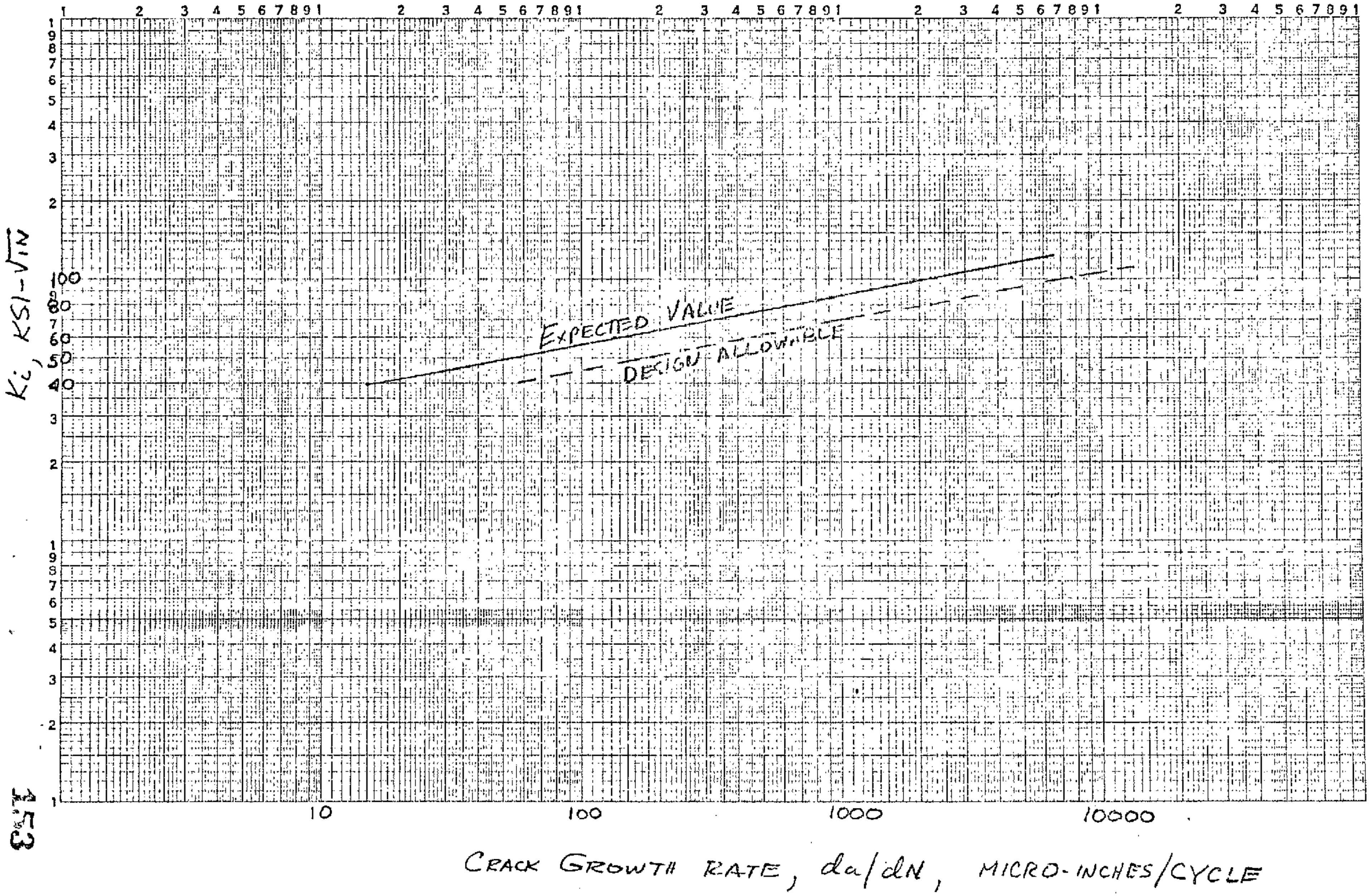
EXPECTED VALUE
DESIGN ALLOWABLE
Ki, KSI-√IN
100
80
60
50
40
10
100
1000
10000
CRACK GROWTH RATE, da/dN, MICRO-INCHES/CYCLE

Figure 2

AEROJET NUCLEAR SYSTEMS COMPANY

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EXPLANATION OF SYMBOLS ON PAGES 2 - 5

s_e = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s_e

PREPARED BY: M Shev

REVIEWED BY P. Newman

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 2/29/72

MATERIAL SS 310 FORM .05" SHEET CONDITION ANNEALED

SPECIFICATIONS QQ-S-766

PROPERTY FATIGUE LIFE @ -320°F

SURFACE FINISH (RMS)	STRESS KSI	LOG OF CYCLES				NO. OF CYCLES (X 10^3)					
		MEAN	s_e	k	99/95 LIMIT	50 % POINT	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
11	80	4.405	.1140	3.64	2.990	25	9.8	5	16	C	1
	77.5	4.804		3.56	4.398	64	25	7			
	75	5.204		3.53	4.802	160	63	8			
	72.5	5.604		3.53	5.202	402	159	8			
	70	6.004		3.56	5.598	1009	396	7			
	67.5	6.404		3.64	5.989	2534	975	5			
64	80	3.890		3.64	3.475	7.8	3.0	5			
	77.5	4.290		3.56	3.885	19	7.7	7			
	75	4.690		3.51	4.290	49	19	9			
	72.5	5.090		3.51	4.690	123	49	9			
	70	5.490		3.53	5.088	309	122	8			
	67.5	5.889		3.59	5.480	775	302	6			
	65	6.289		3.71	5.866	1946	735	4			

MATERIAL SS 310 FORM .05" SHEET CONDITION ANNEALED

SPECIFICATIONS QQ-S-766

PROPERTY FATIGUE STRENGTH @ -320°F

SURFACE FINISH (RMS)	FATIGUE LIFE CYCLES	LOG CYCLES	STRENGTH, KSI MEAN	s_e	k	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
11	3.16×10^4	4.5	79.4	0.71	3.59	76.9	6	16	C	1
	10^5	5.0	76.3		3.53	73.8	8			
	3.16×10^5	5.5	73.2		3.53	70.7	8			
	10^6	6.0	70.0		3.56	67.5	7			
64	10^4	4.0	79.3	0.71	3.59	76.8	6		C	1
	3.16×10^4	4.5	76.2		3.53	73.7	8			
	10^5	5.0	73.1		3.51	70.6	9			
	3.16×10^5	5.5	70.0		3.53	67.5	8			
	10^6	6.0	66.8		3.59	64.3	6			

MATERIAL SS 310 FORM .05" SHEET CONDITION ANNEALED

SPECIFICATIONS QQ-S-766

PROPERTY FATIGUE LIFE @ -423°F

SURFACE FINISH (RMS)	STRESS KSI	LOG OF CYCLES				NO. OF CYCLES (X 10^3)					
		MEAN	s_e	k	99/95 LIMIT	50% POINT	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
11	107.5	3.981	.0822	4.05	3.648	9.6	4.4	2	15	C	1
	105	4.369		3.75	4.061	23	11.5	4			
	102.5	4.757		3.57	4.464	57	29	8			
	100	5.145		3.60	4.849	140	71	7			
	97.5	5.533		3.86	5.216	342	164	3			
	95	5.921		4.05	5.588	835	387	2			
64	105	4.080	.0822	3.86	3.763	12	5.8	3			
	102.5	4.280		3.75	3.972	19	9.4	4			
	100	4.479		3.63	4.181	30	15.2	6			
	97.5	4.678		3.55	4.386	48	24.3	9			
	95	4.877		3.55	4.585	75	39	9			
	92.5	5.076		3.57	4.783	119	61	8			
	90	5.275		3.63	4.977	188	95	6			
	87.5	5.474		3.75	5.166	298	146	4			

MATERIAL SS 310 FORM .05" SHEET CONDITION ANNEALED

SPECIFICATIONS QQ-S-766

PROPERTY FATIGUE STRENGTH @ -423°F

SURFACE FINISH (RMS)	FATIGUE LIFE CYCLES	FATIGUE LIFE LOG CYCLES	STRENGTH, KSI MEAN	STRENGTH, KSI s_e	STRENGTH, KSI k	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
11	10^4	4.0	107.4	0.53	4.05	105.3	2	15	C	1
	3.16×10^4	4.5	104.2		3.68	102.2	5			
	10^5	5.0	101.0		3.57	99.1	8			
	3.16×10^5	5.5	97.7		3.75	95.7	4			
64	10^4	4.0	106.1	1.03	4.05	101.9	2			
	3.16×10^4	4.5	99.8		3.60	96.1	7			
	10^5	5.0	93.5		3.55	89.8	9			
	3.16×10^5	5.5	87.2		3.75	83.3	4			

I. TEST DESCRIPTION

Flexural Reverse Bending Fatigue tests (R=-1) were performed on specimens of SS 310 annealed sheet (.05") by Rocketdyne as described in Reference (1). The sheets were polished to finishes of 11 and 64 rms. Specimens were stamped from the sheets with their longitudinal axis parallel to the sheet rolling direction and normal to the direction of polishing. The specimens were then solution annealed at 1950°F.

Specimens of both finishes were fatigue tested in a constant deflection fatigue machine at both -320°F and -423°F, using operating speeds of 1800 and 2400 cpm respectively. The stress levels were selected to produce failure between 10^4 and 10^7 cycles at -320°F and between 10^4 and 10^6 cycles at -423°F.

The test results were as follows:

Stress, ksi	Cycles to Failure, x 10^3	Stress, ksi	Cycles to Failure, x 10^3
-320°F, 11 rms		-423°F, 11 rms	
82.0	12	107.5	13
79.0	28	105.5	18
77.5	53	104.0	27
75.5	162	102.0	64
75.0	141	102.0	73
72.5	860	101.0	89
72.0	360	100.5	109
69.5	1,258	97.5	331
63.5	10,015 DNF*	95.0	1,005 DNF*
54.5	10,000 DNF**		
-320°F, 64 rms		-423°F, 64 rms.	
80.0	6	103.5	14
78.5	12	101.0	20
78.0	13	101.0	24
77.0	29	100.0	28
76.0	54	98.0	46
75.5	45	95.5	99
70.5	237	94.5	87
70.0	358	94.0	85
66.0	1,288	88.0	400
60.0	10,050 DNF*	79.0	1,015 DNF*

* DID NOT FAIL. Data used as though failure had occurred at number of cycles shown.

** Data not used.

II. DATA ANALYSIS

Regression analysis was used, employing the G.E. computer program MULFIT. The two temperatures were treated separately. Within each temperature, stress level and surface finish were the independent variables, and log of cycles was the dependent variable.

The regression analysis results were:

Temp.	n	Regression Equation*	Standard** Error of Estimate	Index of Determinatic
-320°F	19	$\log y = 17.20 - .1599\, x_1 - .5145\, x_2$	.114	.985
-423°F	19	$\log y = 20.67 - .1552\, x_1 - 8.225\, x_2 + .0756\, x_1 x_2$	.0822	.979

* y = number of cycles to failure
x_1 = stress, ksi
x_2 = surface finish (11 rms = 0; 64 rms = 1)

** in logarithmic units

Both regression equations show a good fit to the data as evidenced by the low standard error of estimate and the high index of determination. The equation for -423°F contains an interaction term which signifies that the S-N curves for the two finishes are not parallel. The equation for -320°F contains no such term, implying parallel S-N curves.

The predicted mean values of log y and the effective sample sizes (n_e) were calculated for a number of different stress levels as shown on Page 2. One-sided 99/95 tolerance limit factors (k) corresponding to the effective sample sizes were determined by means of the computer program TFAC. The 99.95 lower limits were then calculated at each stress level in log units. Finally, both the means and 99/95 limits were converted back to numbers of cycles by taking their anti-logs.* S-N curves are shown in Figures 1 and 2.

* On the assumption that the logarithms are normally distributed, the anti-logs form a non-normal skewed distribution. The anti-log of the mean thus does not correspond with the mean of this distribution, but with its 50% point (or median) and has been so labeled. (Reference 2, Page 43). The anti-log of the 99/95 lower limits are shown as 99/95 design allowables.

On Page 3, the predicted strength for various number of cycles to failure, and the associated n_e, k, and design allowables are shown. The method used to estimate the distribution of strength from the distribution of cycles to failure was an approximate one, but is considered adequate for "C" category data.

III. REFERENCES

1. Rocketdyne Report R-7564, "Fatigue Properties of Sheet, Bar, and Cast Metallic Materials for Cryogenic Applications", dated 30 August 1968

2. ANSC NRP-600, Statistical Distributions, Their Applications and Tables (July, 1970).

FIGURE 1

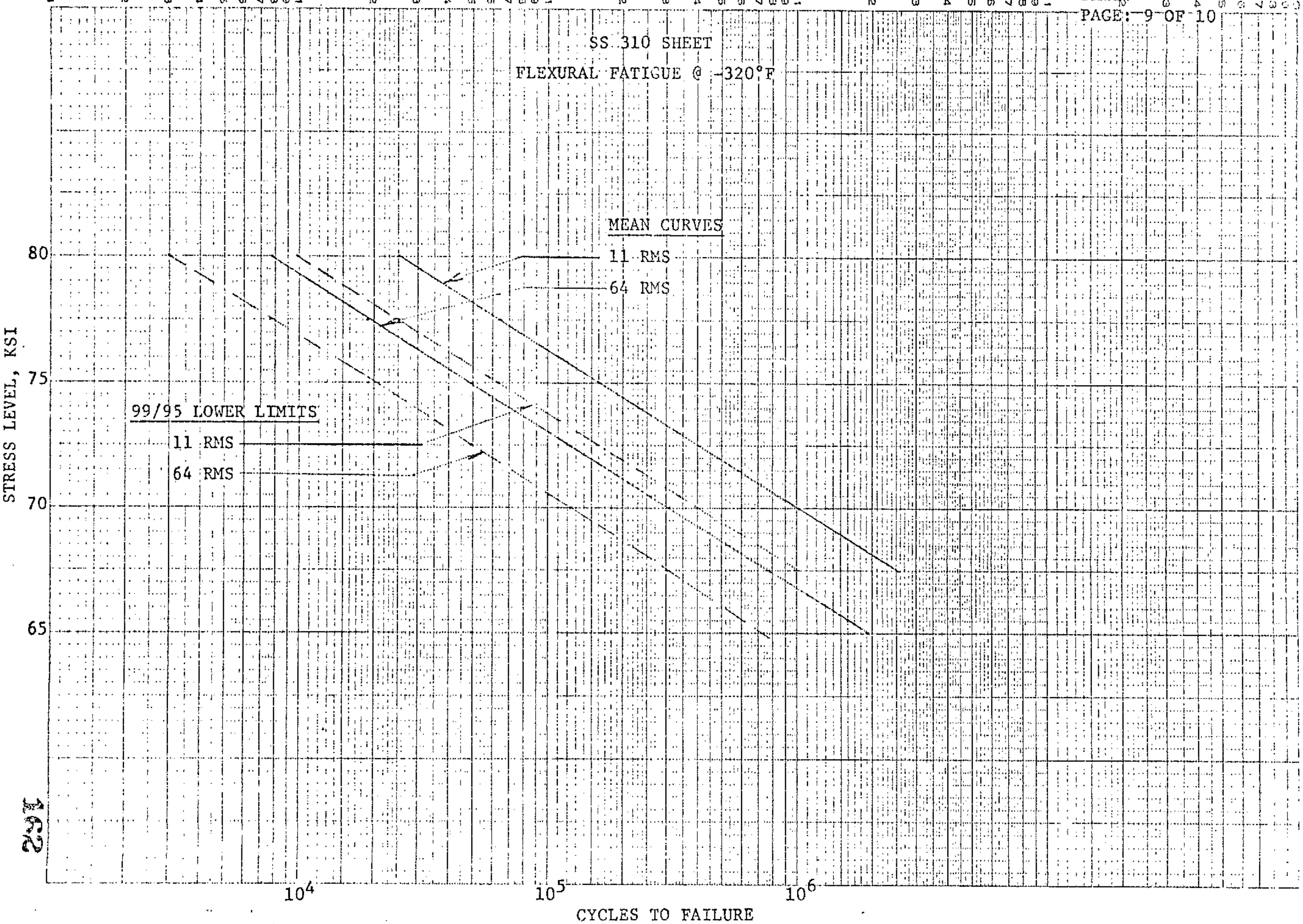
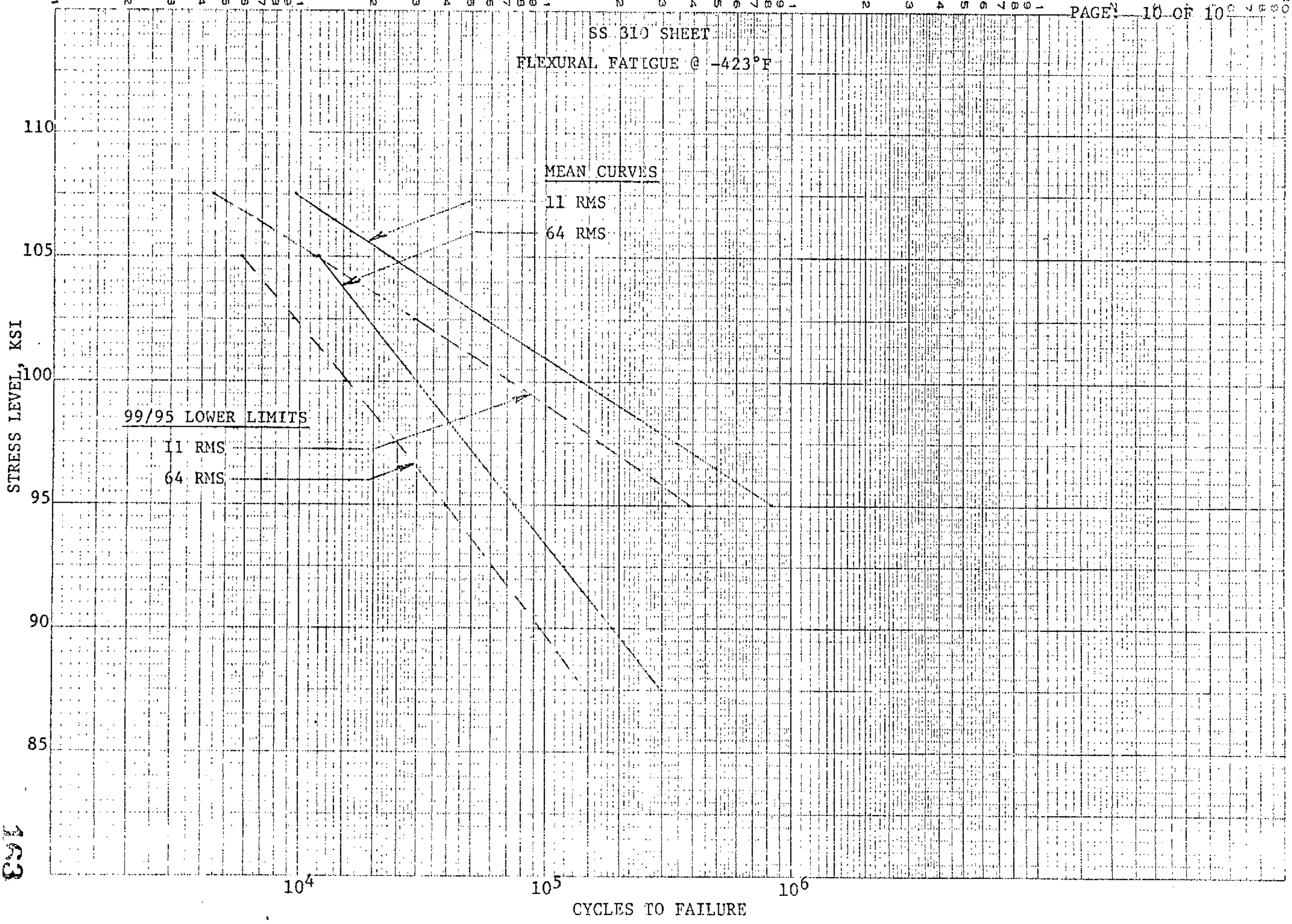

SS 310 SHEET
FLEXURAL FATIGUE @ -320°F
MEAN CURVES
11 RMS
64 RMS
99/95 LOWER LIMITS
11 RMS
64 RMS
80
75
70
65
STRESS LEVEL, KSI
10^4
10^5
10^6
CYCLES TO FAILURE

FIGURE 2


SS 310 SHEET
FLEXURAL FATIGUE @ -423°F
MEAN CURVES
11 RMS
64 RMS
99/95 LOWER LIMITS
11 RMS
64 RMS
STRESS LEVEL, KSI
110
105
100
95
90
85
10^4
10^5
10^6
CYCLES TO FAILURE

AEROJET NUCLEAR SYSTEMS COMPANY

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EXPLANATION OF SYMBOLS ON PAGES 2 AND 3:

- s_e = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)
- k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR
- n_e = EFFECTIVE SAMPLE SIZE
- f = DEGREES OF FREEDOM FOR s_e

PREPARED BY: M Shev

REVIEWED BY: [illegible] 3/2/72

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 3/1/72

MATERIAL SS 310 FORM 3/4" CAST BAR CONDITION ANNEALED

SPECIFICATIONS AMS 5366

PROPERTY AXIAL LOAD FATIGUE LIFE

TEST TEMP °F	STRESS (KSI)	LOG OF CYCLES MEAN	s_e	k	99/95 LOWER LIMIT	CYCLES (X 10^3) 50% POINT	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
RT	60	4.650	.331	4.28	3.233	44.7	1.7	3	9	C	1
	55	4.846		4.12	3.482	70.2	3.0	5			
	50	5.082		4.04	3.745	121	5.6	7			
	45	5.369		3.98	4.052	234	11.3	10			
	40	5.729		4.00	4.405	536	25.4	9			
	35	6.192		4.12	4.828	1555	67.3	5			
	30	6.809		4.46	5.333	6437	215.1	2			
-320	110	4.265	.334	4.78	2.668	18.4	0.5	2	7	C	1
	105	4.418		4.78	2.821	26.2	0.7	2			
	100	4.586		4.60	3.050	38.6	1.1	3			
	95	4.772		4.51	3.266	59.2	1.8	4			
	90	4.979		4.45	3.493	95.2	3.1	5			
	85	5.209		4.38	3.746	162	5.6	7			
	80	5.469		4.35	4.016	295	10.4	8			
	75	5.763		4.35	4.310	580	20.4	8			
	70	6.100		4.45	4.614	1259	41.1	5			
	65	6.488		4.60	4.952	3076	89.5	3			
-423	110	4.909	.163	4.60	4.159	81.1	14.4	2	8	C	1
	105	5.123		4.32	4.419	133	26.2	4			
	100	5.337		4.16	4.659	217	45.6	8			
	95	5.551		4.14	4.876	356	75.2	9			
	90	5.765		4.32	5.061	582	115.0	4			
	85	5.979		4.60	5.229	953	169.5	2			

MATERIAL SS 310 FORM 3/4" CAST BAR CONDITION ANNEALED

SPECIFICATIONS AMS 5366

PROPERTY AXIAL LOAD FATIGUE STRENGTH

TEST TEMP °F	CYCLES	LOG OF CYCLES	RECIPROCAL OF STRESS				STRESS							
			MEAN	s_e	k	99/95 LIMIT	50% POINT	s_e	k	DESIGN ALLOWABLE	n_e	f	DATA CATEGORY	SOURCE REFERENCE
RT	10^5	5.0	.01937	.00256	4.07	.02979	51.6	SEE		33.6	6	9	C	1
	3.16×10^5	5.5	.02323		3.98	.03342	43.0	RECIPROCAL		29.9	10	9		
	10^6	6.0	.02709		4.07	.03751	36.9			26.7	6	9		
	3.16×10^6	6.5	.03095		4.28	.04191	32.3			23.9	3	9		
-320	3.16×10^4	4.5	.00976	.000946	4.78	.01428	102.5			70.0	2	7		
	10^5	5.0	.01117		4.45	.01538	89.5			65.0	5	7		
	3.16×10^5	5.5	.01259		4.35	.01671	79.4			59.8	8	7		
	10^6	6.0	.01400		4.41	.01817	71.4			55.0	6	7		
-423	10^5	5.0	RECIPROCAL NOT USED				107.9	3.81	4.60	90.4	2	8		
	3.16×10^5	5.5					96.2		4.14	80.4	9	8		
	10^6	6.0					84.5		4.60	67.0	2	8		

I. TEST DESCRIPTION

Axial Load (R = 0) fatigue tests at RT, -320°F and -423°F were conducted by Rocketdyne on SS 310 3/4 in. cast bar as described in Reference 1. The material was investment-cast to the specimen configuration and solution annealed at 1900°F. Testing frequency at all three temperatures was 1725 cpm.

Stress levels were selected to cause failure between 10^4 and 10^7 cycles at RT and -320°F and between 10^4 and 10^6 cycles at -423°F.

Test results were as follows:

Maximum Stress, ksi	Cycles to Failure (x 10^3)	Maximum Stress, ksi	Cycles to Failure (x 10^3)	Maximum Stress, ksi	Cycles to Failure (x 10^3)
70 F, Room Temperature		-320 F, Liquid Nitrogen		-423 F, Liquid Hydrogen	
60	30	110	37	110	47
55	422	100	43	105	244
50	129	90	91	102.5	151
50	140	80	122	97.5	289
45	96	75	339	97.5	465
45	156	70	460	95	229
45	177	70	735	95	437
40	215	67.5	5,184	92.5	508
35	995	65	10,406 DNF*	90	367
35	3,437	60	10,008 DNF**	86	914
30	10,900 DNF*				

* DID NOT FAIL. Data point used as though failure had occurred at the number of cycles shown.

** DID NOT FAIL. Data point not used.

II. DATA ANALYSIS

The method of regression analysis, employing the G.E. computer program MULFIT,was used. The three temperatures were treated separately. Regression analysis results were:

Temp.	n	Regression Equation *	Standard Error** of Estimate	Index of Determination
RT	11	$\log y = 2.491 + 129.53\ (1/x)$	.331	.780
-320°F	9	$\log y = 1.054 + 353.21\ (1/x)$	.334	.823
-423°F	10	$\log y = 9.617 - .0428\ x$	.163	.761

* y = number of cycles to failure
x = stress, ksi

** in logarithmic units

The equations for room temperature and -320°F contain the reciprocal transform of stress. At these temperatures, this model showed a better fit to the data than the linear model (as shown for -423°F) or a model employing the log of stress.

The predicted mean values of log y and the effective sample sizes (n_e) were calculated for a number of different stress levels as shown on Page 2. One-sided 99/95 tolerance limit factors (k) corresponding to the effective sample sizes were determined by means of the computer program TFAC. The 99/95 lower limits were then calculated at each stress level in log units. Finally, both the means and 99/95 limits were converted back to numbers of cycles by taking their anti-logs. S-N curves are shown in Figures 1 and 2.

On Page 3, the predicted strength for various number of cycles to failure, and the associated n_e, k, and design allowables are shown. The method used to estimate the distribution of strength from the distribution of cycles to failure was an approximate one, but is considered adequate for "C" category data.

For RT and -320°F, the 99/95 limits were first calculated in reciprocal stress units. Finally, the means and 99/95 limits were converted back to ksi units.

III. REFERENCES

1. Rocketdyne Report R-7564, "Fatigue Properties of Sheet, Bar and Cast Metallic Materials for Cryogenic Applications", dated 30 August 1968.

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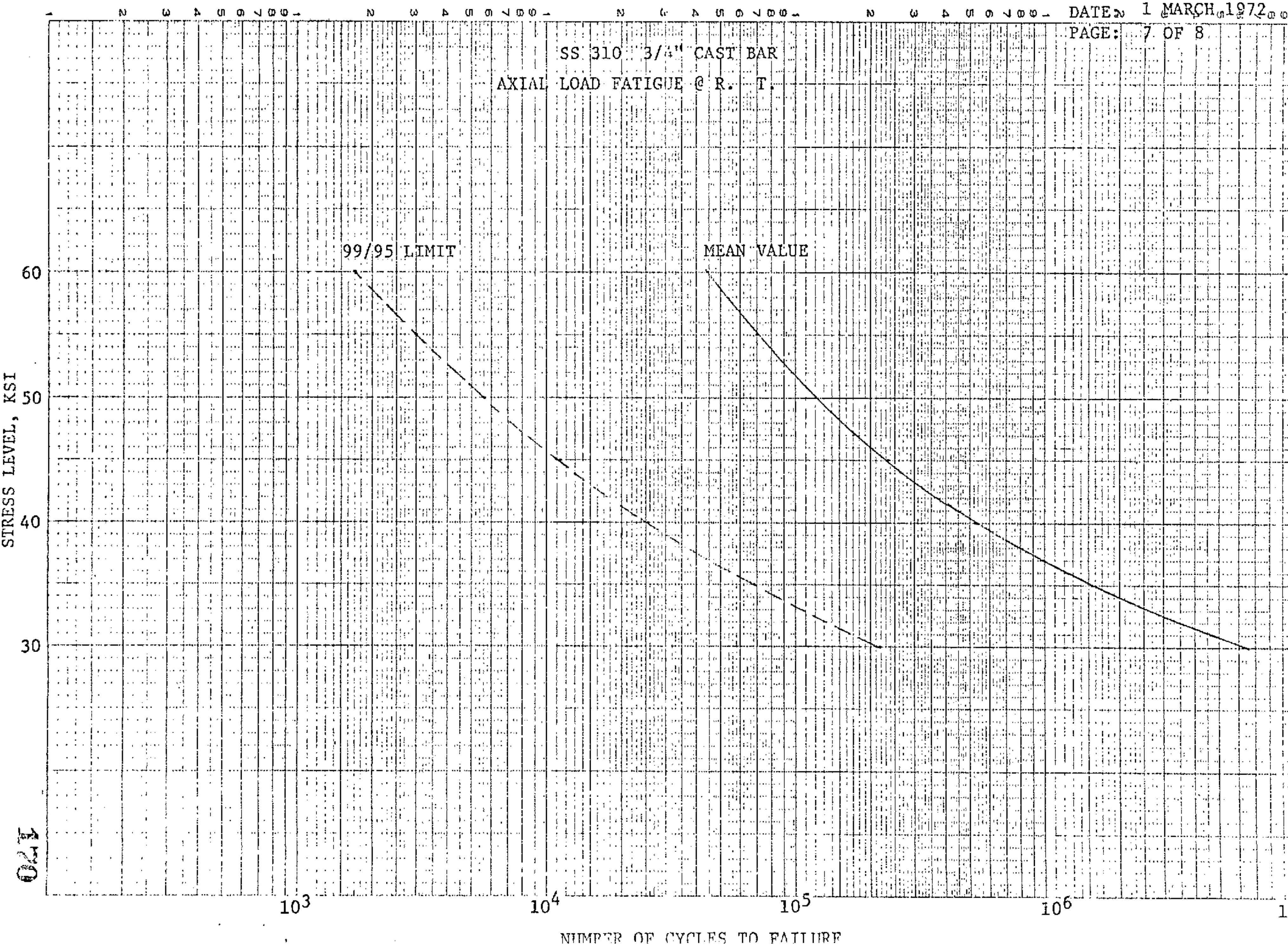
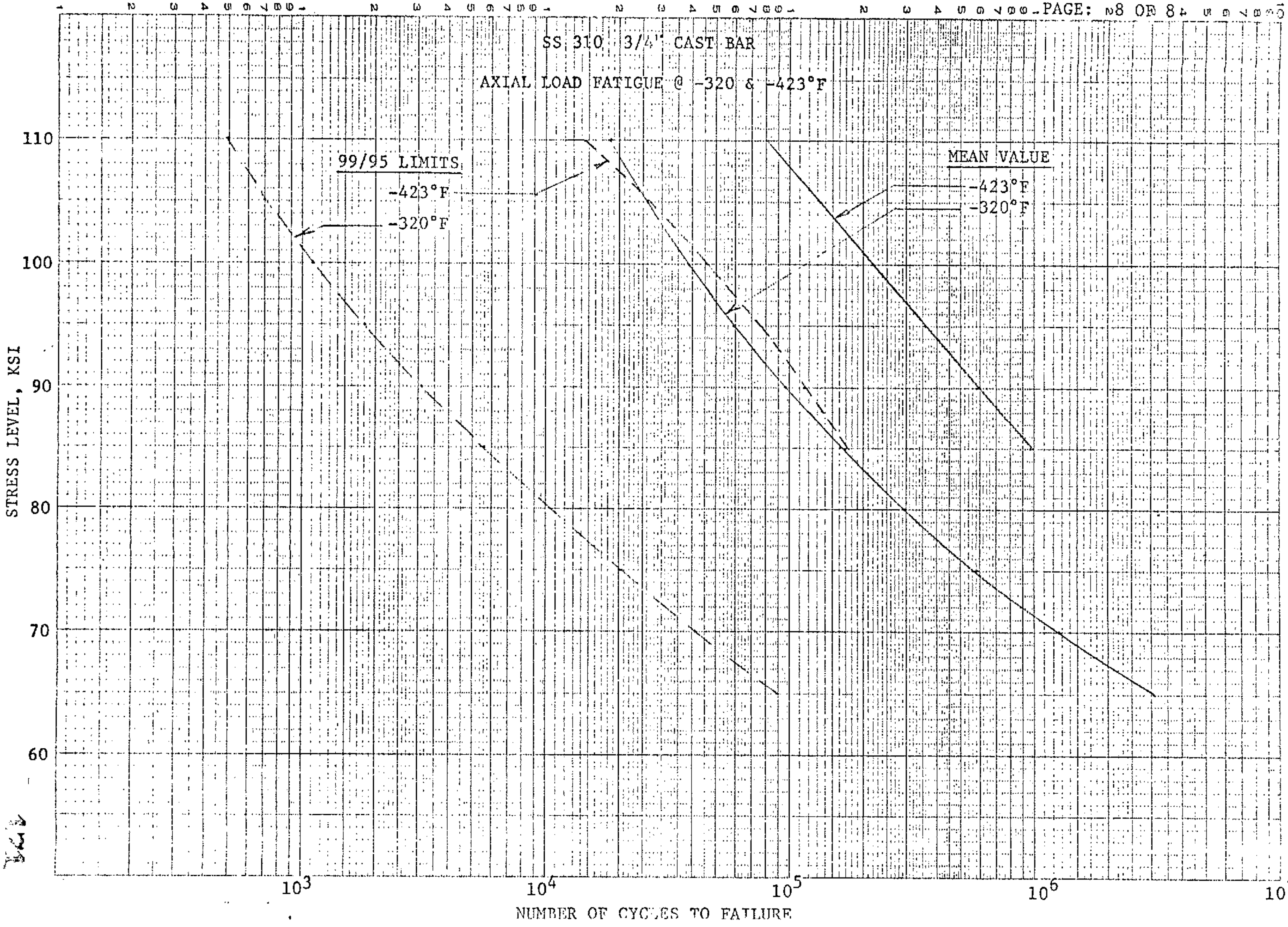
FIGURE 1



F20

FIGURE 2


SS 310 3/4" CAST BAR
AXIAL LOAD FATIGUE @ -320 & -423°F
99/95 LIMITS
-423°F
-320°F
MEAN VALUE
-423°F
-320°F
STRESS LEVEL, KSI
110
100
90
80
70
60
10^3
10^4
10^5
10^6
10^7
NUMBER OF CYCLES TO FAILURE

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MATERIALS DATA RELEASE

CONTENTS

SYMBOLS USED ON PAGES 2 - 4

m = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR COMBINED STANDARD DEVIATION, s_T

k = 99/95 LOWER TOLERANCE LIMIT FACTOR FOR m AND f

PREPARED BY: M Shev

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 3/24/72

MATERIAL SS 310 FORM PANCAKE FORGINGS CONDITION "A" (ANNEALED & QUENCHED)

SPECIFICATIONS QQ-S-763 DIRECTION TANGENTIAL

PROPERTY ULTIMATE TENSILE STRENGTH @ RT, KSI

NO. OF OBSERVATIONS	NO. OF* FORGINGS	NO. OF HEATS	VARIANCE AMONG FORGINGS	VARIANCE WITHIN FORGINGS	VARIANCE TOTAL s_T^2	MEAN** VALUE $\bar{X}$	m	f	k	s_T	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
108	36	2	0.870	0.369	1.240	82.46	5	39	3.30	1.11	78.8	A	1

* 4 EACH OF 9 DIFFERENT CONFIGURATIONS

** LOWEST MEAN OF THE 9 CONFURATIONS

MATERIAL SS 310 FORM PANCAKE FORGINGS CONDITION "A" (ANNEALED & QUENCHED)

SPECIFICATIONS QQ-S-763 DIRECTION TANGENTIAL

PROPERTY 0.2% YIELD TENSILE STRENGTH @ RT, KSI

NO. OF OBSERVATIONS	NO. OF* FORGINGS	NO. OF HEATS	VARIANCE			MEAN** VALUE							
			AMONG FORGINGS	WITHIN FORGINGS	TOTAL s_T^2	$\bar{X}$	m	f	k	s_T	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
108	36	2	0.990	7.870	8.860	42.04	9	92	2.99	2.98	33.0	A	1

* 4 EACH OF 9 DIFFERENT CONFIGURATIONS

** LOWEST MEAN OF THE 9 CONFIGURATIONS

MATERIAL SS 310 FORM PANCAKE FORGINGS CONDITION "A" (ANNEALED & QUENCHED)

SPECIFICATIONS QQ-S-763 DIRECTION TANGENTIAL

PROPERTY ELONGATION @ RT, %

NO. OF OBSERVATIONS	NO. OF* FORGINGS	NO. OF HEATS	VARIANCE AMONG FORGINGS	VARIANCE WITHIN FORGINGS	VARIANCE TOTAL s_T^2	MEAN** VALUE $\bar{X}$	m	f	k	s_T	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
108	36	2	1.73	2.75	4.88	46.02	60	86	2.73	2.12	40.2	A	1

* 4 EACH OF 9 DIFFERENT CONFIGURATIONS

** GRAND MEAN OF ALL CONFIGURATIONS

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I. TEST DESCRIPTION (PER REFERENCE (1))

Room temperature tensile data were obtained on ten different configurations of SS 310 pancake forgings for TPA housings. The forgings were made by West Coast Forge using vacuum arc remelt material containing a maximum of 0.08% carbon. The material for 8 of the configurations was from Heat No. 10623 and the other two from Heat No. 10621. The forgings were brought to the "A" condition by annealing at 1900°F for one hour followed by water quenching.

The tensile data were obtained from material certifications (Enclosures (1) to (10) of Reference (1)). Four forgings of each configuration were used in the preparation of tensile specimens. Three specimens*, all tangentially oriented, were prepared and tested from each forging.

The part numbers, forging dimensions, and average tensile properties are shown in the following table:

---

* Except for P/N 1139354-1 as noted below.

P/N	DIAMETER IN.	THICKNESS IN.	ULTIMATE STRENGTH KSI	YIELD STRENGTH KSI	ELONGATION %
*1139354-1	6.00	6.30	85.5	43.7	46.0
1139370-1	12.88	8.20	84.2	44.3	46.3
**1139371-1	18.50	9.00	82.8	45.5	45.8
1139372-1	14.75	9.25	84.0	42.0	45.4
1139373-1	11.65	2.65	83.6	44.1	47.3
**1139374-1	18.12	9.12	83.3	45.8	45.8
1139375-1	14.75	3.81	86.6	42.3	46.1
1139376-1	17.62	3.25	83.2	43.3	45.8
1139377-1	8.84	2.72	85.0	47.8	44.5
1139379-1	15.38	7.50	82.5	43.1	47.2

* 2 specimens tested per forging; all others 3 per forging

** from Heat No. 10621; all others from Heat No. 10623

II. DATA ANALYSIS

The data matrix represents a nested design in which the effects are: Configurations (a fixed variable), forgings within configurations (a random variable), and replicates (specimens within forgings, a random variable). There is no obvious correlation between properties and forging size, and no apparent difference in properties between the two heats. Furthermore, there is no way of separating the possible effect of heats from the effect of configurations.

The first configuration, P/N 1139354, with only two specimens tested per forging, was excluded from the analysis to avoid the complexity introduced by unequal sample sizes. Since this configuration exhibited typical properties, its exclusion does not appreciably affect the results.

Analysis of variance was performed with the aid of the G.E. computer and resulted in the following ANOVA tables:

PROPERTY	SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F
Ultimate Strength	Configurations	155.16	8	19.39	6.51*
	Forgings	80.47	27	2.98	8.07*
	Replicates	26.60	72	0.369	
	Total	262.23	107		
Yield Strength	Configurations	334-69	8	41.84	3.86*
	Forgings	292.70	27	10.84	1.38
	Replicates	566.67	72	7.87	
	Total	1194.06	107		
Elongation	Configuration	65.46	8	8.18	1.04
	Forgings	212.50	27	7.87	2.86*
	Replicates	198.00	72	2.75	
	Total	475.96	107		

* Significant, .05 level

These tables indicate a significant variation among configurations for the first two properties, but not for elongation. Because configuration is a fixed, rather than a random variable, it can be deleted as a variable of classification for elongation per the guidelines of Reference (2).* Rather than nine configurations with four forgings each, there are simply 36 forgings, and the simplified ANOVA is as follows:

PROPERTY	SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F
Elongation	Forgings	277.96	35	7.94	2.88*
	Replicates	198.00	72	2.75	
	Total	475.96	107		

The components of variance, the effective sample size, m, and the effective degrees of freedom, f, were calculated by means of the computer program SATT**. The corresponding 99/95 tolerance limit factor, k, was determined by means of the computer program TFALT, and finally the design allowable for elongation was calculated as $\bar{X}-ks_T$.

* "Any fixed variable whose effects are not significant at the $\alpha = 0.05$ level may be deleted as a variable of classification".

** Satterthwaite's approximation.

For the other two properties, for which the configurations differed significantly, the method of the Lowest Lot Mean, an alternate method of Reference (3), was used. The standard deviation, s_T, which combines within-forging and among-forging variability over all the configurations, was calculated. The appropriate value of f was determined by means of the Satterthwaite equation. The appropriate m, however, was based on one configuration only, and the design allowables were calculated as $\bar{X}_L - ks_T$ where $\bar{X}_L$ is the mean of the configuration having the lowest mean for the property.

The data are classified as "A" because they meet the requirements of TD 69-28 and TD 69-37, as amended, (Reference (2)) including the use of two material lots.

III. <u>REFERENCES</u>

1. Memorandum N8130:0174, from P. P. Dessau to H. Derow, dated 6 October 1971 Subject: "AISI 310 Stainless Steel Pancake Forging Data".

2. Letter, L. C. Corrington (SNSO-C) to W. O. Wetmore (ANSC), dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data".

3. NERVA Program Procedure, R101-NRP-503, Statistical Analysis of Material Test Data.

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MATERIALS DATA RELEASE

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MATERIAL	FORM	CONDITION	PROPERTY	DATA CATEGORY	PAGE
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			CYCLES TO VARIOUS Ki LEVELS		3
			CYCLIC FRACTURE TOUGHNESS		4
			CRACK GROWTH RATE		5

(IN GH_2 @ RT, 1200 PSI AND LH_2 @ -423°F)

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PREPARED BY: M Shev

REVIEWED BY: A J Bisnump

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 5/19/72

MATERIAL AISI 9310 FORM BAR CONDITION CARBURIZED

SPECIFICATIONS AMS 6265

PROPERTY STATIC FRACTURE TOUGHNESS, K_{IC}, Ki - IN

TEST TEMP.	K_{IC} (KSI - IN) MEAN	n	s*	DESIGN ** ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-423°F	32.2	1	3	23.2	C	1
RT	45.0	1	3	36.0	C	1

* ESTIMATED

** CONSERVATIVE ENGINEERING ESTIMATE

MATERIAL AISI 9310 FORM BAR CONDITION CARBURIZED

SPECIFICATIONS AMS 6265

PROPERTY CYCLES TO VARIOUS K_i LEVELS

TEST TEMP.	K_i KSI - $\sqrt{\text{IN}}$	LOG OF CYCLES MEAN	s	n_e	f	LOWER* LIMIT	NUMBER OF CYCLES 50% POINT	DESIGN* ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-423°F	15	4.023	.123	1	1	3.654	10537	4508	C	1
	20	3.121	.123	2	1	2.752	1320	565		
	25	2.219	.123	1	1	1.850	165	71		
RT	10	5.016	.0670	1	1	4.815	103834	65300	C	1
	20	3.878		3	1	3.677	7556	4755		
	30	3.366		4	1	3.165	2323	1462		
	40	3.071		3	1	2.870	1179	741		
	50	2.882		2	1	2.681	762	480		
	60	2.753		1	1	2.552	566	356		
	70	2.662		1	1	2.461	459	289		

* CONSERVATIVE ENGINEERING ESTIMATE RATHER THAN 99/95 ALLOWABLES. SAMPLE SIZE WAS INSUFFICIENT TO OBTAIN REASONABLE 99/95 k VALUES.

MATERIAL AISI 9310 FORM BAR CONDITION CARBURIZED

SPECIFICATIONS AMS 6265

PROPERTY CYCLIC FRACTURE TOUGHNESS, Ki, KSI - $\sqrt{IN}$

TEST TEMP.	NO. OF CYCLES	Ki (KSI - $\sqrt{IN}$) MEAN	s	k**	DESIGN* ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-423°F	100	26.2	0.7	3	24.2	C	1
	1000	20.7	0.7		18.7		
	10000	15.1	0.7		13.1		
RT	1000	43.3	2.8		24.0	C	1
	10000	18.4	0.8		16.0		
	100000	10.1	0.4		9.0		

* CONSERVATIVE ENGINEERING ESTIMATE, NOT 99/95 LIMITS.

** k ASSUMED TO BE 3 FOR PURPOSES OF CALCULATING s

MATERIAL AISI 9310 FORM BAR CONDITION CARBURIZED

SPECIFICATIONS AMS 6265

PROPERTY CRACK GROWTH RATE, da/dN, MICRO-INCHES/CYCLE

TEST TEMP.	Ki (KSI - $\sqrt{IN}$)	K_{IC} (da/dN) MEAN	s	n_e	f	k	99/95 UPPER LIMIT	da/dN 50% POINT	da/dN DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
-423°F	12	0.629	0.447	4	34	3.41	2.153	4	142	C	1
	16	1.195		12		3.12	2.590	16	389		
	20	1.946		32		3.00	3.287	88	1936		
	24	2.760		29		3.01	4.105	576	12749		
	28	3.691		15		3.09	4.972	3897	93806		
RT	20	1.668	0.127	2	28	3.78	2.148	47	141	C	1
	30	1.991		4		3.47	2.432	100	270		
	40	2.234		8		3.27	2.649	172	446		
	50	2.417		15		3.15	2.817	261	656		
	60	2.566		24		3.10	2.960	368	911		
	70	2.692		29		3.08	3.083	492	1211		
	80	2.801		27		3.09	3.193	633	1561		
	90	2.898		21		3.11	3.293	790	1963		
	100	2.984		16		3.14	3.383	963	2414		
	110	3.062		12		3.19	3.467	1153	2932		
	120	3.133		10		3.22	3.542	1358	3483		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington, under ANSC P.O. N-01499.

One lot of AISI 9310 bar per AMS 6265, Heat No. 392344 procured from Earle M. Jorgenson & Company, Oakland, California, was used in the test program. The material was carburized per instructions in ANSC P.O. N-01309 by Pacific Steel Heat Treat, Los Angeles. Fracture toughness specimens were fabricated from the bar stock so as to maintain the flaw propagation direction of the specimens parallel to the extruding direction. A total of 14 specimens were fabricated and testing was conducted at room temperature and at -423°F.

A total of 6 specimens were tested in GH_2 and 4 specimens were tested in GHe to note the effect of hydrogen on the toughness of the material. In addition, 4 specimens were tested in LH_2. Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. The test matrix, giving the test conditions and number of specimens tested was as follows:

Test Type	Test Environment (1200 psig)		
	GHe Room Temp.	GH_2 Room Temp.	LH_2 -423°F
Static Fracture	1	1	1
Cyclic Fracture	3	5	3

From these results, a Ki versus number of cycles to failure curve was developed for each test condition. In addition, instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test.

The test results were as follows: (Tests in Hydrogen only).

Specimen Number	Test Environment	No. of Cycles	Ki or K_{IC} KSI - IN
880002	GH_2	1 (K_{IC})	82.2
880003	LH_2	1 (K_{IC})	32.2
880010	GH_2	430	65.9
880008	GH_2	1019	48.4
880006	GH_2	6182	20.4
880011	GH_2	4580	18.7*
880009	GH_2	100001	10.2
880012	LH_2	118	25.2
880014	LH_2	1406	20.8
880013	LH_2	22840	12.8

* Freq. = 1 cps. Data point not used. Balance of tests were at 5 cps.

In addition, instantaneous crack growth data were supplied by Boeing on computer printouts, up to 22 pairs of observations (da/dN vs Ki) per specimen.

2. DATA ANALYSIS

a. Fracture Toughness

The static fracture toughness tests yielded valid K_{IC} data and are reported on Page 2. An estimated standard deviation of 3 KSI - $\sqrt{IN}$ was used to calculate conservative engineering limits rather than 99/95 design allowables. There was a marked hydrogen embrittlement effect. Therefore, only the hydrogen data, the worst case, are reported.

Regression analysis, with the aid of the G.E. computer program MULFIT was used for the cyclic fracture toughness data.

At -423°F, a linear equation (Ki vs log cycles) was found to fit the data well. The results were as follows:

n	Regression Equation	s_e*	R^2
3	log N = 6.729 - .1804 Ki	.123	.983

* in logarithmic units.

This equation was used to calculate expected values of log N for various Ki levels from 15 to 25 KSI - $\sqrt{IN}$. Because of the small sample size, useful 99/95 limits could not be calculated. Instead conservative engineering limits are shown. Finally both expected values and limits were converted to anti-log units (number of cycles) (Page 3). To place the data in a more useful form, the equation was back-solved to yield expected and allowable Ki's for various numbers of cycles. These are given on Page 4.

At room temperature, although tests were conducted in both GH_2 and GHe, only the hydrogen data were used because these represent the worst case. The following quadratic equation was found to fit the data very well.

n	Regression Equation	s_e	R^2
4	$\log N = 11.174 - 7.985 (\log Ki) + 1.827 (\log Ki)^2$	.0670	.995

This equation was used to calculate expected values of log N for various Ki levels from 10 to 70 KSI - IN. Because of the small sample size, however, useful 99/95 limits could not be calculated. Instead, conservative engineering limits are shown. The equation was then back-solved to yield expected and allowable Ki's for various numbers of cycles. The data are shown graphically in Figures 1 and 2.

b. Crack Growth Data da/dN

(1) -423°F

The data from the computer printout were divided into two groups, above and below da/dN = 100 microinches/cycle. It was possible to find a satisfactory linear fit (Eq. 1) only for the lower group, the scatter being excessive in the higher group. For the purposes of design allowable calculation, all the data were combined and a quadratic equation (Eq. 2) fitted. Results were:

	n	Regression Equation *	s_e **	R^2
Eq. 1: (da/dN < 100)	16	$\log y = -4.868 + 5.062 \log x$	.196	.794
Eq. 2: (all data)	37	$\log y = 14.544 - 28.512 \log x + 14.472 (\log x)^2$	.447	.786

(2) Room Temperature

Because of the extreme embrittlement effect, only the hydrogen data are reported. The usual pattern of two different slopes was not in evidence, so a single linear equation was determined as follows:

n	Regression Equation *	s_e **	R^2
30	$\log y = - 0.782 + 1.883 \log x$	.127	.852

* y = da/dN, microinches/cycle

** in logarithmic units

These equations were used to calculate expected values of log (da/dN) for various Ki levels. Design allowables were then calculated in the usual manner. The results are plotted in Figure 3.

3. REFERENCES

(1) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

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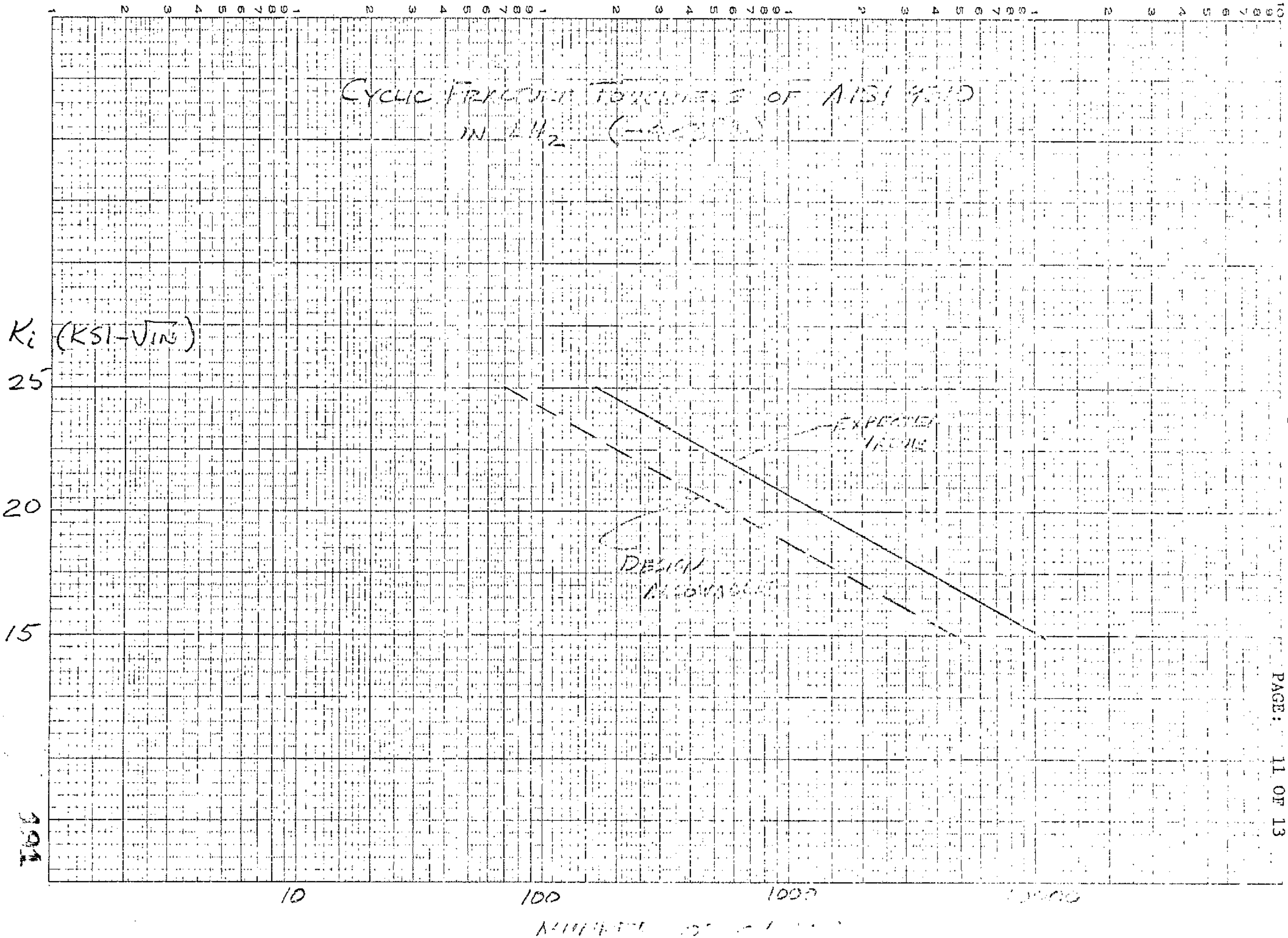

Figure 1

DRM: 31.03
DATE: 17 MAY 1972
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NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

EUGENE DIETZGEN CO.
MADE IN U. S. A.

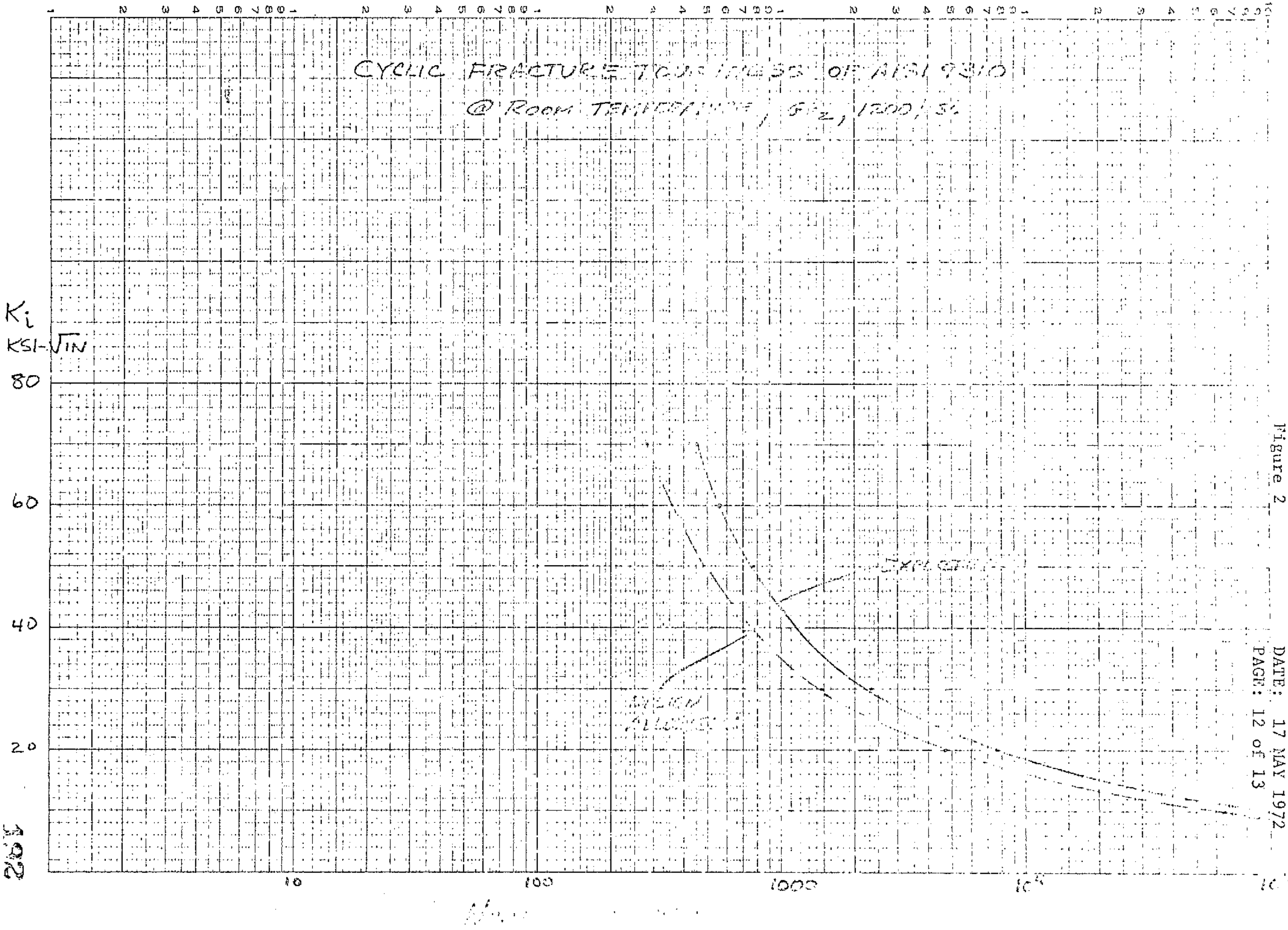

Figure 2

DRM: 31.03
DATE: 17 MAY 1972
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CRACK GROWTH RATE OF AISI 9310

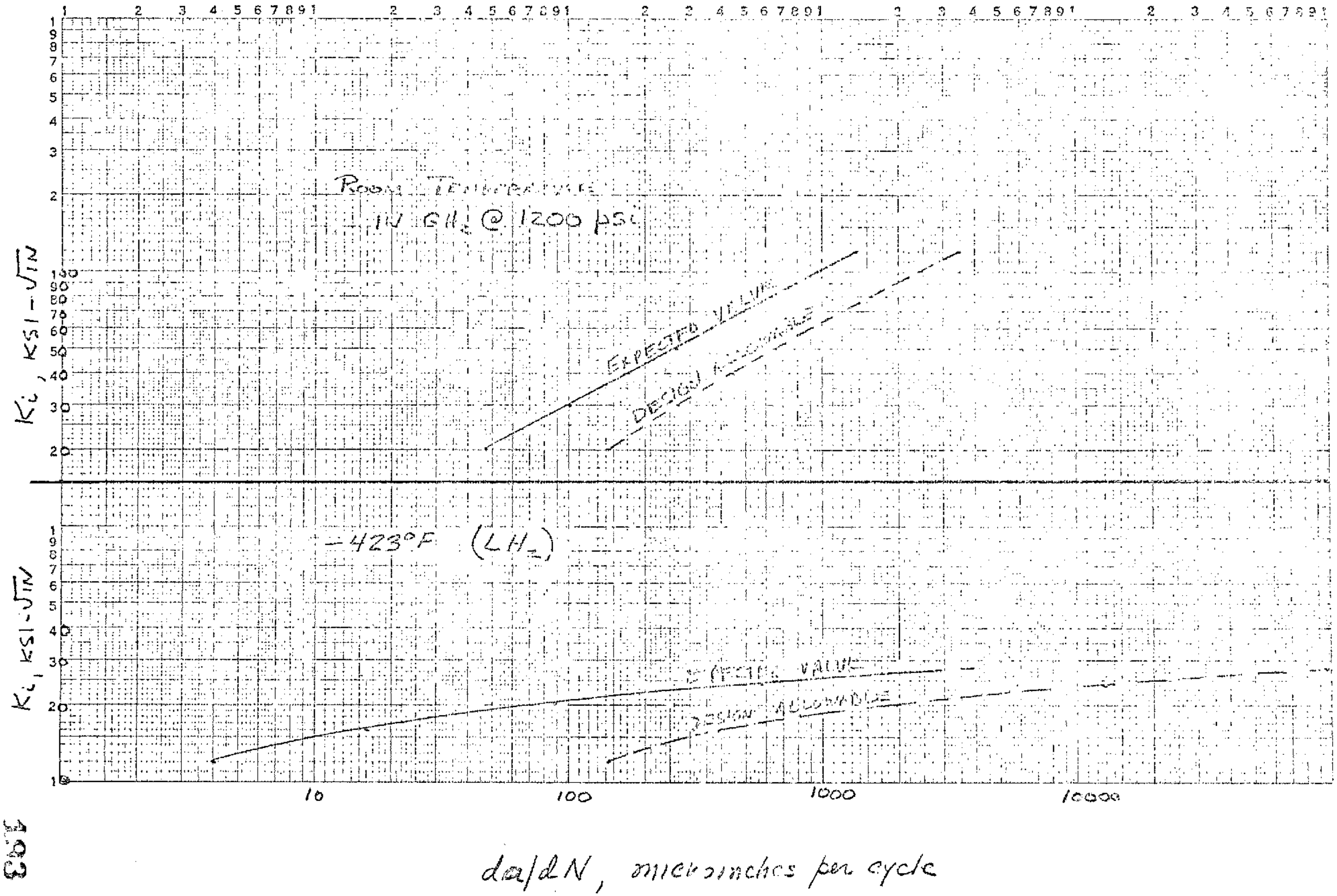

Figure 3

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DATE: 17 MAY 1972
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AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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THIS REVISION SUPERSEDES DRM 37.02 DATED 2 FEBRUARY 1971

PREPARED BY:

REVIEWED BY:

CLASSIFICATION:

UNCLASSIFIED

PER

DATE 3/24/72

MATERIAL PHOSPHOR BRONZE "A" FORM ALL CONDITION ALL

SPECIFICATIONS

PROPERTY LINEAR THERMAL EXPANSION, %

TEMP., °F	NOMINAL* VALUE	STANDARD DEVIATION s	k***	99/95 LIMITS**	DATA CATEGORY	SOURCE REFERENCE
-423	-0.330	.0064	2.576	-0.313 TO -0.346	C	1
-400	-0.329	.0064		-0.313 TO -0.345		
-350	-0.318	.0062		-0.302 TO -0.334		
-300	-0.296	.0057		-0.281 TO -0.311		
-250	-0.267	.0052		-0.254 TO -0.280		
-200	-0.232	.0045		-0.220 TO -0.244		
-150	-0.194	.0038		-0.184 TO -0.204		
-100	-0.152	.0030		-0.144 TO -0.160		
- 50	-0.107	.0021		-0.102 TO -0.112		
0	-0.062	.0012		-0.059 TO -0.065		

* PERCENT CHANGE IN LENGTH FROM 68°F

** NOMINAL ± 5%

*** BASED ON NORMAL CURVE (INFINITE DEGREES OF FREEDOM)

MATERIAL PHOSPHOR BRONZE "A" FORM ALL CONDITION ALL

SPECIFICATIONS

PROPERTY MEAN COEFFICIENT OF THERMAL EXPANSION (α), IN/IN/°F X 10^6

TEMP., °F	NOMINAL VALUE	STANDARD DEVIATION s	k**	99/95 LIMITS*	DATA CATEGORY	SOURCE REFERENCE
FROM 68 TO -423	6.72	0.13	2.576	6.38 TO 7.06	C	1
FROM 68 TO -400	7.03	0.14		6.68 TO 7.38		
FROM 68 TO -350	7.61	0.15		7.23 TO 7.99		
FROM 68 TO -300	8.04	0.16		7.64 TO 8.44		
FROM 68 TO -250	8.40	0.16		7.98 TO 8.82		
FROM 68 TO -200	8.66	0.17		8.23 TO 9.09		
FROM 68 TO -150	8.90	0.17		8.46 TO 9.34		
FROM 68 TO -100	9.05	0.18		8.60 TO 9.50		
FROM 68 TO - 50	9.07	0.18		8.62 TO 9.52		
FROM 68 TO 0	9.12	0.18		8.66 TO 9.58		

* NOMINAL ± 5%

** BASED ON NORMAL CURVE (INFINITE DEGREES OF FREEDOM)

I. TEST DESCRIPTION

Thermal expansion of Phosphor Bronze A between liquid hydrogen temperature and room temperature was measured by the Cryogenics Divsion, National Bureau of Standards, Boulder, Colorado, and is reported in Reference (1). The condition of the sample is described as "Spring Cold Drawn 85%" with a Rockwell "B" hardness of 91. The apparatus and the method used are described in Reference (1).

II. DATA ANALYSIS

The data are assumed to apply to all forms and conditions of the alloy. Measurements were reported in degrees K. A series of temperatures in °F (-423, and -400 to 0 in 50° increments) were converted to the Kelvin Scale and interpolated from a plot of the NBS data for thermal expansion in inches per inch. The mean coefficient of thermal expansion was obtained by dividing these values by the temperature difference from 68°F.

The upper and lower limits were calculated as these nominals $\pm$ 5%, an uncertainty band which has been recommended (Reference (2)) for those physical properties that exhibit little or no material variability. The limits have been conventionally designated "99/95" and the associated tolerance limit, k, assumed to be 2.576, per the guidelines of Reference (3). A working estimate of the standard deviation was obtained at each temperature by dividing the difference between the nominal and the limit by k. (Reference (3)).

III. REFERENCES

(1) A. F. Clark (NBS, Boulder), "Low Temperature Thermal Expansion of Some Metallic Alloys", Cryogenics Vol. 8, No. 5, October 1968.

(2) Letter 7732:ML70-343, ANSC to SNPO-C dated 21 September 1970, Subject: "Material Properties Data Book Meeting, SNPO-C, 18-19 August 1970".

(3) Letter L. C. Corrington (SNSO) to W. O. Wetmore (ANSC) dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data (Enclosure (3), Para. 12).

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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EXPLANATION OF SYMBOLS ON PAGES 2 - 4

s = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

PREPARED BY: M Shev

REVIEWED BY: Peter P. [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER M Shev

DATE 5/9/72

MATERIAL PHOSPHOR BRONZE FORM BAR CONDITION HARD

SPECIFICATIONS AMS 4625

PROPERTY NUMBER OF CYCLES FOR VARIOUS K1 LEVELS

	LOG OF CYCLES						NUMBER OF CYCLES			
K1 (KSI $-\sqrt{IN}$)	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
30	4.267	.100	3	12	4.01	3.866	18509	7345	C	1
40	3.765		6	12	3.80	3.385	5832	2427		
50	3.264		11	12	3.68	2.896	1838	787		
60	2.763		13	12	3.66	2.397	579	249		
70	2.261		8	12	3.73	1.888	182	77		
80	1.760		4	12	3.91	1.369	57	23		

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MATERIAL PHOSPHOR BRONZE FORM BAR CONDITION HARD

SPECIFICATIONS AMS 4625

PROPERTY CYCLIC FRACTURE TOUGHNESS, K_I, KSI - $\sqrt{\text{IN}}$

NUMBER OF CYCLES	K_I, KSI - $\sqrt{\text{IN}}$ MEAN	s	n_e	f	k	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
1 (Kq)	88.8	4 *	2	-	-	76.8 **	C	1
100	75.2	1.89	6	12	3.80	68.0		
1000	55.3	1.99	13	12	3.66	48.0		
10000	35.3	2.16	5	12	3.85	27.0		

* ESTIMATED FROM OTHER MATERIALS

** 3-SIGMA LOWER LIMIT; NOT 99/95 LIMIT

MATERIAL PHOSPHOR BRONZE FORM BAR CONDITION HARD

SPECIFICATIONS AMS 4625

PROPERTY CRACK GROWTH RATE, da/dN, MICRO-INCHES PER CYCLE

Ki (KSI - $\sqrt{IN}$)	LOG (da/dN) MEAN	s	n_e	f	k	99/95 UPPER LIMIT	da/dN 50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
30	0.764	.107	9	57	3.06	1.091	6	12	C	1
40	1.344	.107	22	57	2.90	1.654	22	45		
50	1.794	.107	50	57	2.83	2.097	62	125		
60	2.161	.107	54	57	2.82	2.463	145	290		
70	2.471	.107	34	57	2.86	2.777	296	598		
80	2.940	.268	30	47	2.91	3.720	871	5247		
90	3.424	.268	47	47	2.88	4.196	2653	15698		
100	3.856	.268	22	47	2.94	4.644	7183	44047		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington, under ANSC P.O. N-01499.

One lot of Phosphor Bronze bar per AMS 4625, (hard condition) procured from Alaskan Copper and Brass Company, Seattle, Washington, was used in the test program. Fracture toughness specimens were fabricated from the bar stock so as to maintain the flaw propagation direction of the specimens parallel to the extruding direction. A total of 12 specimens were fabricated and testing was conducted at room temperature.

A total of 7 specimens were tested in GH_2 and 5 specimens were tested in GHe to note the effect of hydrogen on the toughness of the material. Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. The test matrix, giving the test conditions and number of specimens tested was as follows:

Test	Test Environment (1200 psig)	
Type	GHe	GH_2
Static Fracture	1	1
Cyclic Fracture	4	6

From these results, a Ki versus number of cycles to failure curve was developed for each test condition. In addition, instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test.

The test results were as follows:

Specimen Number	Test Environment	No. of Cycles	Ki KSI - $\sqrt{IN}$
880103	GH_2	1	88.6
880104	GHe	1	89.0
880102	GH_2	190	70.7
880105	GHe	3725	42.9
880106	GHe	22508	29.1
880107	GH_2	247	66.0
880107	GH_2	2370	46.5
880108	GHe	1210	54.0
880109	GHe	314	67.8
880110	GH_2	238	70.1
880110	GH_2	98	78.5
880111	GH_2	23	83.7
880111	GH_2	983	55.2
880112	GH_2	1198	50.9
880112	GH_2	26998	28.0
880113	GH_2	878	55.8

As seen from this table, four of the specimens generated two observations each. In addition, instantaneous crack growth data were supplied by Boeing on computer printouts, up to 17 pairs of observations (da/dN vs Ki) per specimen.

2. DATA ANALYSIS

a. Fracture Toughness

The two static fracture toughness tests failed to yield valid K_{IC} data. Instead they are reported as a special case of Ki, at one cycle. There was no appreciable difference between the tests in helium and hydrogen; therefore the two were combined.

Regression analysis, with the aid of the G.E. computer program MULFIT was used for the cyclic fracture toughness data. An attempt was made to use the static test results in the same regression equation, but no simple function was found which would fit the combined data without a large increase in the standard error of estimate. The one cycle data reported on Page 2 merely represent the average of the 2 static tests. The standard deviation of 4 is a conservative estimate from other materials, and the design allowable shown is an engineering estimate (3-sigma) rather than a 99/95 limit.

A linear equation (Ki vs log cycles) was found to fit both the hydrogen and the helium data very well. The results were as follows:

n	Regression Equation	s_{e}*	R^2
14	log N = 5.772 - .05015 Ki	.100	.985

* in logarithmic units.

This equation was used to calculate expected values of log N for various Ki levels from 30 to 80 KSI -$\sqrt{\text{IN.}}$ The 99/95 lower limits were calculated in the usual manner and finally both expected values and limits were converted to anti-log units (number of cycles). To place the data in a more useful form, the equation was back-solved to yield expected and allowable Ki's for various numbers of cycles. These are given on Page 3. The results are shown in Figure 1.

b. Crack Growth Rate (da/dN)

The data from the computer printouts were divided into two groups, below and above Ki = 75. These represent the two slopes of the lines relating log (da/dN) as a function of Ki. The computer program MULFIT was used to determine the least squares regression lines. The analysis was first done separately for the hydrogen and helium groups, but when no appreciable difference was found they were combined.

The results were:

	n	Regression Equation*	s_e**	R^2
Ki $\leq$ 75	59	log y = -6.088 + 4.63 log x	.107	.962
Ki > 75	49	log y = -15.054 + 9.455 log x	.268	.775

* y = da/dN, micro-inches per cycle
x = Ki, KSI-$\sqrt{\text{in.}}$
** in logarithmic units.

These equations were used to calculate expected values of log (da/dN) for various Ki levels. Design allowables were then calculated in the usual manner. The results are plotted in Figure 2.

3. REFERENCES

(1) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

EUGENE DIETZGEN CO.
MADE IN U. S. A.

CYCLIC FRACTURE TOUGHNESS OF PHOSPHOR BRONZE @ ROOM TEMPERAURE

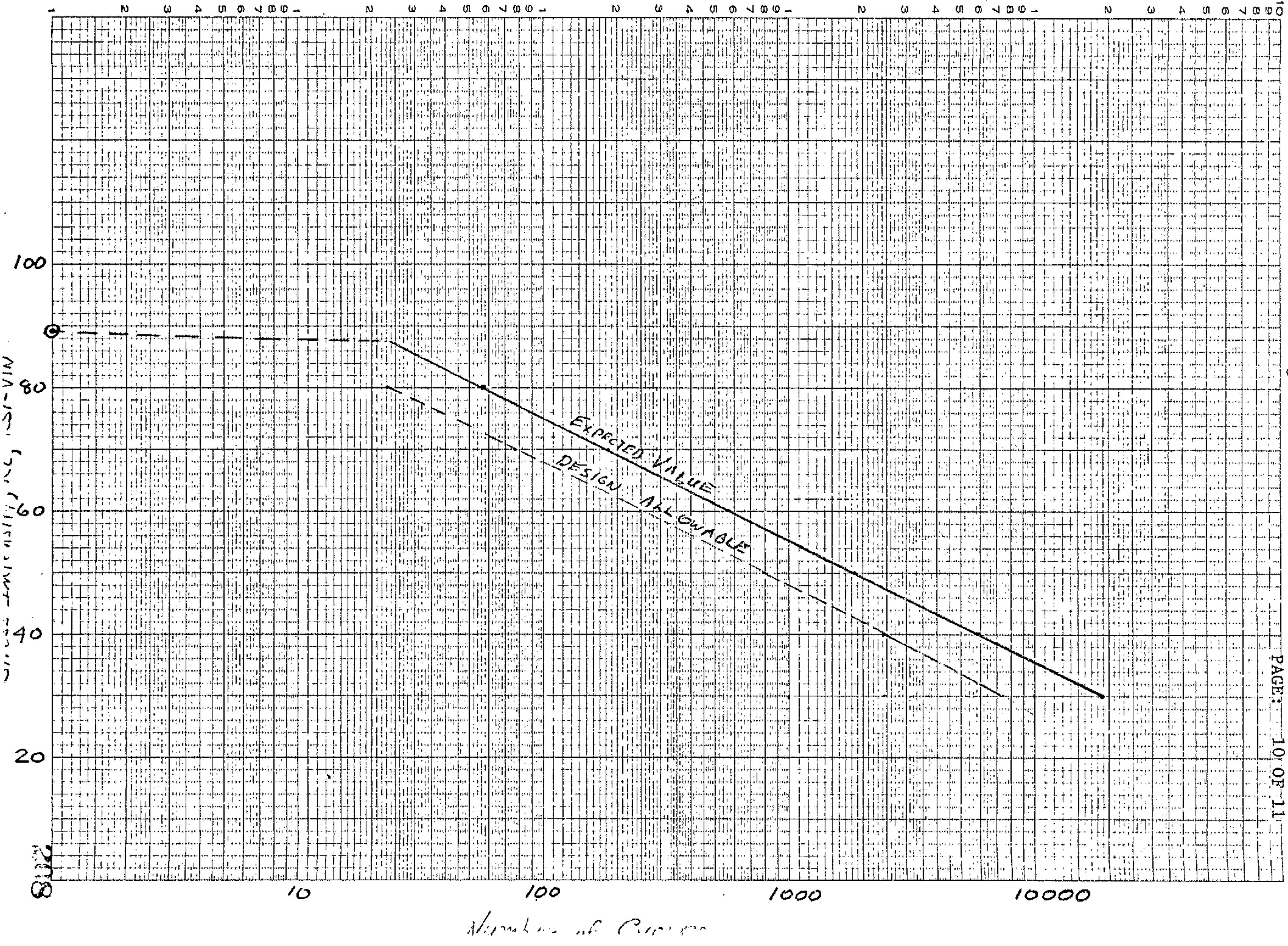

Figure 1

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DATE: 9 MAY 1972
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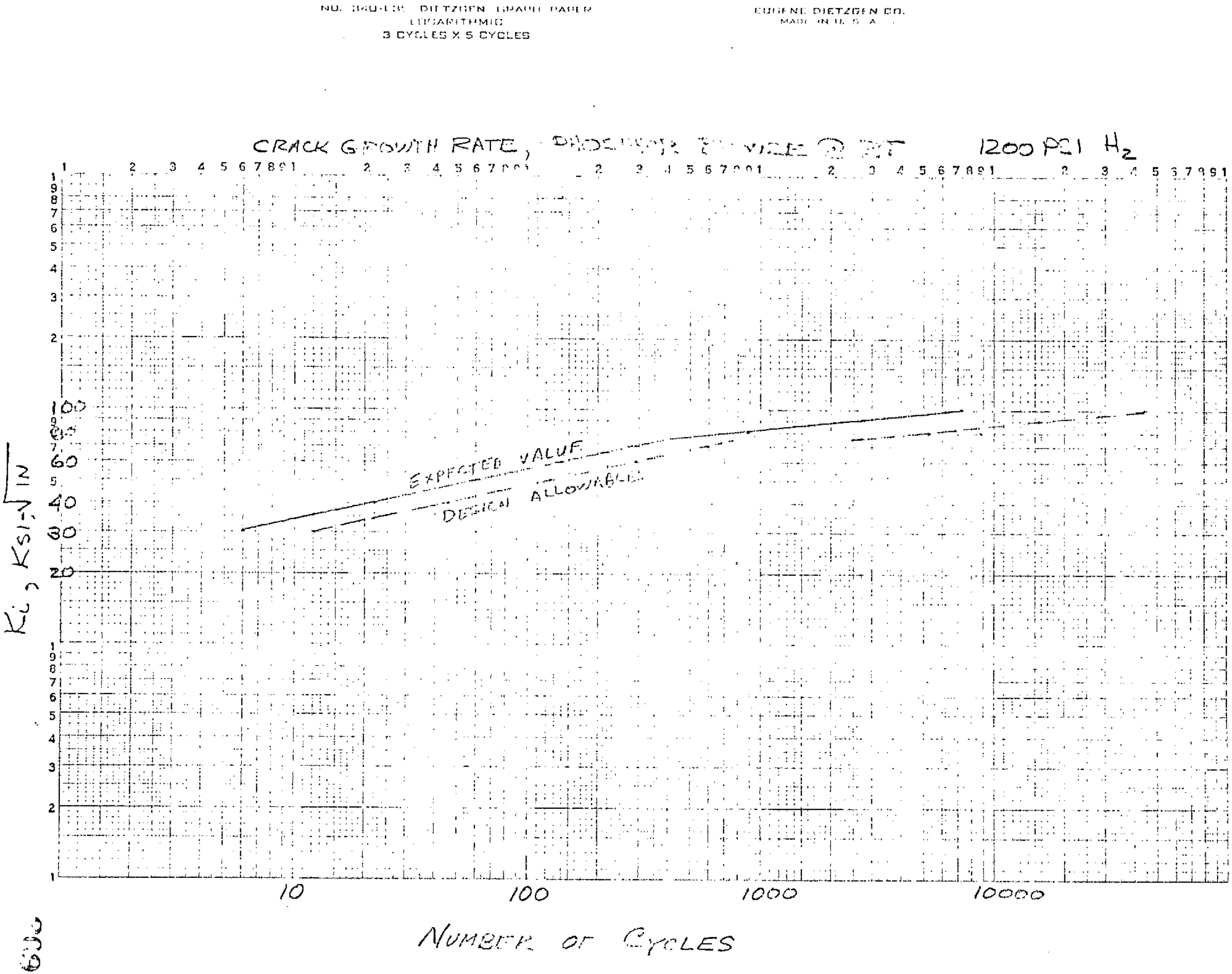

Figure 2

DRM: 37.04
DATE: 9 MAY 1972
PAGE: 11 OF 11

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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PREPARED BY: M. Shev

REVIEWED BY: [illegible]

CLASSIFICATION:

UNCLASSIFIED

PER: M Shev

DATE 3/21/72

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MATERIAL ALLOY 22-13-5 FORM ALL CONDITION ALL

SPECIFICATIONS

PROPERTY DYNAMIC MODULUS, PSI (X 10^6)

TEMPERATURE °F	NO. OF OBSERVATIONS	MEAN VALUE $\overline{X}$	STANDARD DEVIATION s	DEGREES OF FREEDOM f	TOLERANCE LIMIT FACTOR k	DESIGN ALLOWABLES LOWER	DESIGN ALLOWABLES UPPER	DATA CATEGORY	SOURCE REFERENCE
-320	4	31.35	0.54	9	4.68	28.8	33.9	C	1
RT	4	29.63	0.54	9	4.68	27.1	32.2	C	1
600	4	26.31	0.54	9	4.68	23.8	28.8	C	1

MATERIAL ALLOY 22-13-5 FORM ALL CONDITION ALL

SPECIFICATION

PROPERTY POISSON'S RATIO

TEMPERATURE °F	NO. OF OBSERVATIONS	MEAN VALUE $\bar{X}$	STANDARD DEVIATION s	DEGREES OF FREEDOM f	TOLERANCE LIMIT FACTOR k	DESIGN ALLOWABLES LOWER	DESIGN ALLOWABLES UPPER	DATA CATEGORY	SOURCE REFERENCE
-320	4	0.2735	.0046	9	4.68	0.252	.295	C	1
RT	4	0.2850	.0046	9	4.68	0.264	.306	C	1
600	4	0.2998	.0046	9	4.68	0.278	.321	C	1

I. TEST DESCRIPTION

Dynamic Modulus and Poisson's ratio of Alloy 22-13-5 at -320°F, RT, and 600°F were measured by WANL per ANSC P. O. N-01728. The material submitted for testing was 8" X 1 1/4" plate in the simulated furnace-brazed condition.

A single test specimen, per ANSC P/N 1138310, was fabricated from the material and used for all the determinations. An ultrasonic technique, described in Reference (1), was used. Four determinations were made at each of the three temperatures. The results are reported in Reference (2) and are considered to apply to all forms and conditions of Alloy 22-13-5. Averages for each temperature are shown on pages 2 and 3.

II. DATA ANALYSIS

Normally, design values for these physical properties would be reported as nominal $\pm$ 5%. (Reference (3)). However, since the replicate determinations provide a measure of experimental error variability, the design values were calculated as true 99/95 limits. All variability is attributed to test error rather than to the material.

The within-temperature variances were found to be homogeneous by means of the Bartlett-Box test and accordingly were pooled into a single variance estimate, s^2, based on 9 degrees of freedom. Two-sided tolerance limit factors, k, were determined from Reference (4). Finally, 99/95 limits were calculated as $\overline{X} \pm ks$.

III. REFERENCES

1. WANL Test Plan 38-10, Project 485G, dated 5 August 1971.

2. Letter from R. F. Dickson (WANL) to J. L. Dooling (ANSC) dated 22 October 1971, Subject: "Project 485, Test Plan M-38 Line 10, Requisition No. N-01728: Dynamic Modulus Tests.

3. Letter from L. C. Corrington (SNSO-C) to W. O. Wetmore (ANSC) dated 5 January 1972, Subject: "Classification, Interpretation and Use of Materials Property Data".

4. A. Weissberg and G. H. Beatty, "Tables of Tolerance - Limit Factors for Normal Distributions", Technometrics, Vol. 2, No. 4 p 483-500 (1960).

AEROJET NUCLEAR SYSTEMS COMPANY

MATERIALS DATA RELEASE

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EXPLANATION OF SYMBOLS ON PAGES 2 - 4

s = STANDARD DEVIATION (STANDARD ERROR OF ESTIMATE)

n_e = EFFECTIVE SAMPLE SIZE

f = DEGREES OF FREEDOM FOR s

k = 99/95 ONE-SIDED TOLERANCE LIMIT FACTOR

PREPARED BY: M. Shiv

REVIEWED BY: C. J. Beinengo

CLASSIFICATION:

UNCLASSIFIED

PER M.S.

DATE 5/10/72

MATERIAL ALLOY 22-13-5 FORM PLATE CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS

PROPERTY NUMBER OF CYCLES TO VARIOUS Ki LEVELS

	LOG OF CYCLES						NUMBER OF CYCLES			
Ki (KSI-$\sqrt{\text{IN}}$)	MEAN	s	n_e	f	k	99/95 LOWER LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
40	4.316	.0437	1	7	5.22	4.088	20703	12243	C	1
50	3.855		4	7	4.51	3.658	7158	4549		
60	3.442		9	7	4.34	3.252	2766	1788		
70	3.077		6	7	4.41	2.884	1194	766		
80	2.761		3	7	4.60	2.560	576	363		

MATERIAL ALLOY 22-13-5 FORM PLATE CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS

PROPERTY CYCLIC FRACTURE TOUGHNESS, Ki, KSI - $\sqrt{IN}$

NUMBER OF CYCLES	Ki, KSI - $\sqrt{IN}$ MEAN	s	n_e	f	k	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
1	121.0	4 *	-	-	-	109.0*	C	1
1000	72.3	1.30	5	7	4.45	66.5		
10000	43.7	1.02	3	7	4.60	42.0		

* CONSERVATIVE ENGINEERING ESTIMATE, NOT 99/95 LIMIT.

MATERIAL ALLOY 22-13-5 FORM PLATE CONDITION SIMULATED FURNACE BRAZE

SPECIFICATIONS

PROPERTY CRACK GROWTH RATE, da/dN, MICRO-INCHES PER CYCLE @ RT

	LOG (CRACK GROWTH RATE)						CRACK GROWTH RATE			
Ki (KSI -$\sqrt{IN}$)	MEAN	s	n_e	f	k	UPPER 99/95 LIMIT	50% POINT	DESIGN ALLOWABLE	DATA CATEGORY	SOURCE REFERENCE
50	1.141	.158	11	63	3.00	1.615	14	41	C	1
60	1.580	.158	23	63	2.88	2.035	38	108		
70	1.952	.158	47	63	2.81	2.396	89	249		
80	2.274	.158	64	63	2.79	2.715	188	519		
90	2.557	.158	47	63	2.81	3.001	361	1002		
100	2.811	.158	29	63	2.85	3.261	648	1825		
110	3.218	.248	15	26	3.18	4.007	1653	10154		
120	3.626	.248	26	26	3.12	4.400	4226	25105		
130	4.001	.248	10	26	3.25	4.807	10021	64121		

1. TEST DESCRIPTION

This DRM is based upon work performed by the Boeing Aerospace Group, Seattle, Washington, under ANSC P. O. N-01499.

One lot of ARMCO 22-13-5 stainless steel plate procured from ARMCO Steel Corporation, Baltimore, Maryland, was used in this test program. The material was subjected to a final heat treat (simulated furnace braze cycle) by Pyromet. Fracture toughness specimens were fabricated from the bar stock so as to maintain the flaw propagation direction of the specimens parallel to the extruding direction. A total of 12 specimens were fabricated and testing was conducted at room temperature.

A total of 7 specimens were tested in GH_2 and 5 specimens were tested in GHe to note the effect of hydrogen on the toughness of the material. Both static (K_{IC}) and cyclic (Ki) fracture toughness tests were conducted. The test matrix, giving the test conditions and number of specimens tested was as follows:

Test Type	Test Environment (1200 psig)	
	GHe	GH_2
Static Fracture	1	1
Cyclic Fracture	4	6

From these results, a Ki versus number of cycles to failure curve was developed for each test condition. In addition, instantaneous crack growth rate (crack growth per cycle) data was developed for each Ki test.

The test results were as follows:

Specimen Number	Test Environment	No. of Cycles	Ki KSI - IN
880075	GHe	1	124.3
880076	GH_2	1	117.8
880077	GHe	2084	63.7
880077	GHe	12085	30.7
880078	GHe	10381	47.9
880080	GHe	1835	66.4
880082	GHe	553	79.1
880081	GH_2	1508	66.9
880083	GH_2	568	81.3
880079	GH_2	10241	46.7
880084	GH_2	9268	46.2
880085	GH_2	1448	67.1
880086	GH_2	2607	59.1
880086	GH_2	2	129.3

As seen from this table, two of the specimens generated two observations each. In addition, instantaneous crack growth data were supplied by Boeing on computer printouts, up to 15 pairs of observations (da/dN vs Ki) per specimen.

2. DATA ANALYSIS

a. Fracture Toughness

The two static fracture toughness tests failed to yield valid K_{IC} data. Instead they are reported as a special case of Ki, at one cycle. There was no appreciable difference between the tests in helium and hydrogen; therefore the two were combined.

Regression analysis, with the aid of the G.E. computer program MULFIT was used for the cylic fracture toughness data. An attempt was made to use the static test results in the same regression equation, but no simple function was found which would fit the combined data without a large increase in the standard error of estimate. The one cycle data reported on Page 2 merely represent the average of the 2 static tests. The standard deviation of 4 is a conservative estimate from other materials, and the design allowable shown is an engineering estimate (3-sigma) rather than a 99/95 limit.

A quadratic equation (Ki vs log cycles) was found to fit both the hydrogen and the helium data very well and slightly better than a linear equation. The results were as follows:

n	Regression Equation	s_e*	R^2
10**	$\log N = 6.644 - .06785\, Ki + 2.414 \times 10^{-4}\, Ki^2$	.0437	.991

* in logarithmic units

** Two of the data points, the second observations on specimens 88077 and 88086 failed to fit the curve and were excluded as outliers.

This equation was used to calculate expected values of log N for various Ki levels from 40 to 80 KSI - $\sqrt{IN}$. The 99/95 lower limits were calculated in the usual manner and finally both expected values and limits were converted to anti-log units (number of cycles). To place the data in a more useful form, the equation was back-solved to yield expected and allowable Ki's for 100 and 1000 cycles. These are given on Page 3. Results are plotted in Figure 1.

b. Crack Growth Rate (da/dN)

The data from the computer printouts were divided into two groups, below and above Ki = 105. These represent the two slopes of the lines relating log (da/dN) as a function of Ki. The computer program MULFIT was used to determine the two least squares regression lines. The analysis was first done separately for the hydrogen and helium groups, but when no appreciable difference was found they were combined.

The results were:

	n	Regression Equation*	s_e**	R^2
Ki $\leq$ 105	65	log y = -8.288 + 5.550 log x	.158	.910
Ki > 105	28	log y = -18.804 + 10.788 log x	.248	.673

* y = da/dN, micro-inches per cycle; x = Ki

** in logarithmic units.

These equations were used to calculate expected values of log (da/dN) for various Ki levels. Design allowables were then calculated in the usual manner. The results are plotted in Figure 2.

3. REFERENCES

(1) "Flaw Growth of Various NERVA Engine Materials", by W. D. Bixler, Aerospace Group, The Boeing Company, March 1972.

CYCLIC FRACTURE TOUGHNESS OF ALLOY 22-13-5 at Room Temp.

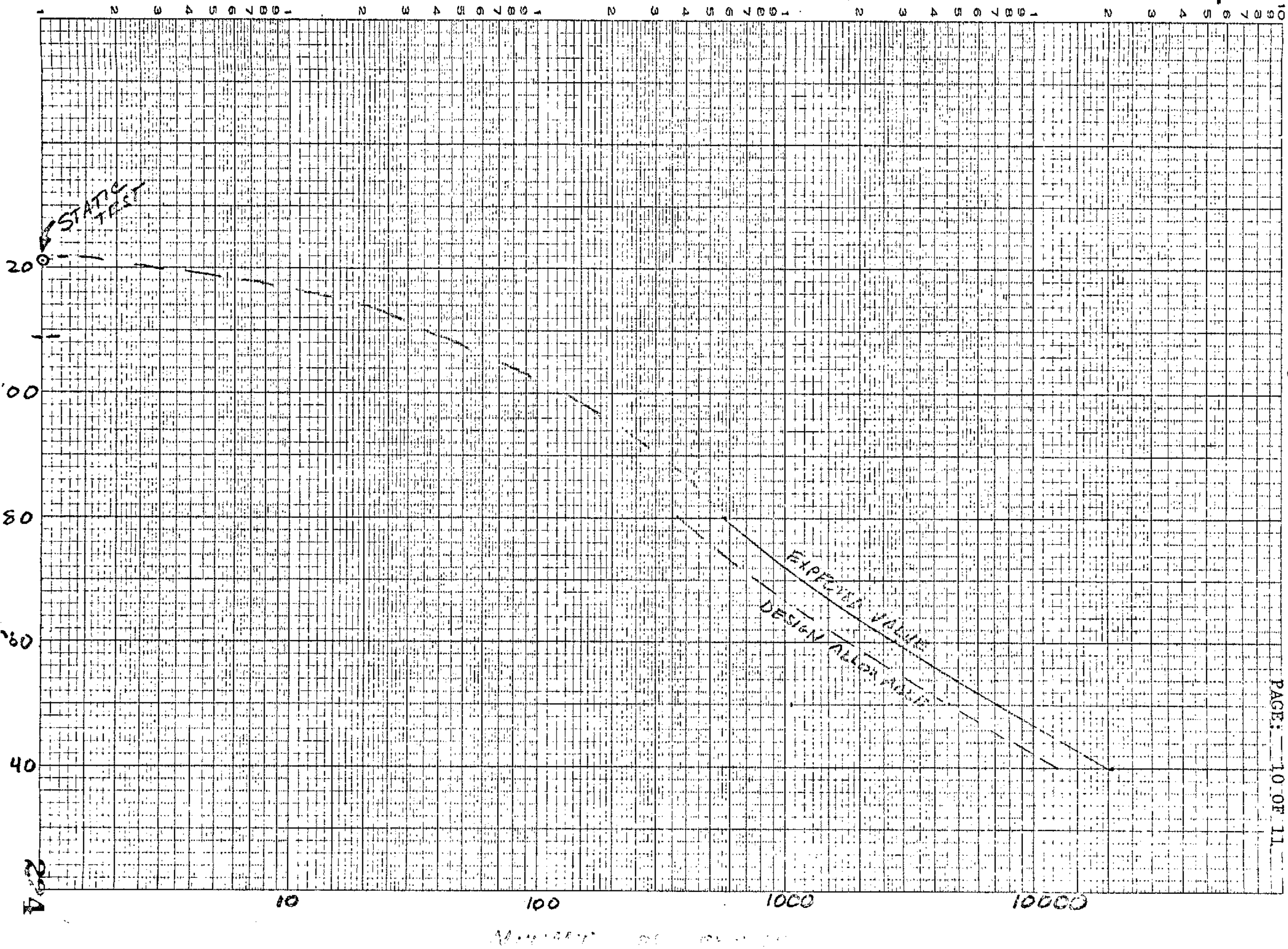

Figure 1

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CRACK GROWTH RATE OF ALLOY 22-13-5 @ ROOM TEMPERATURE IN GH_2, 1200 PSI

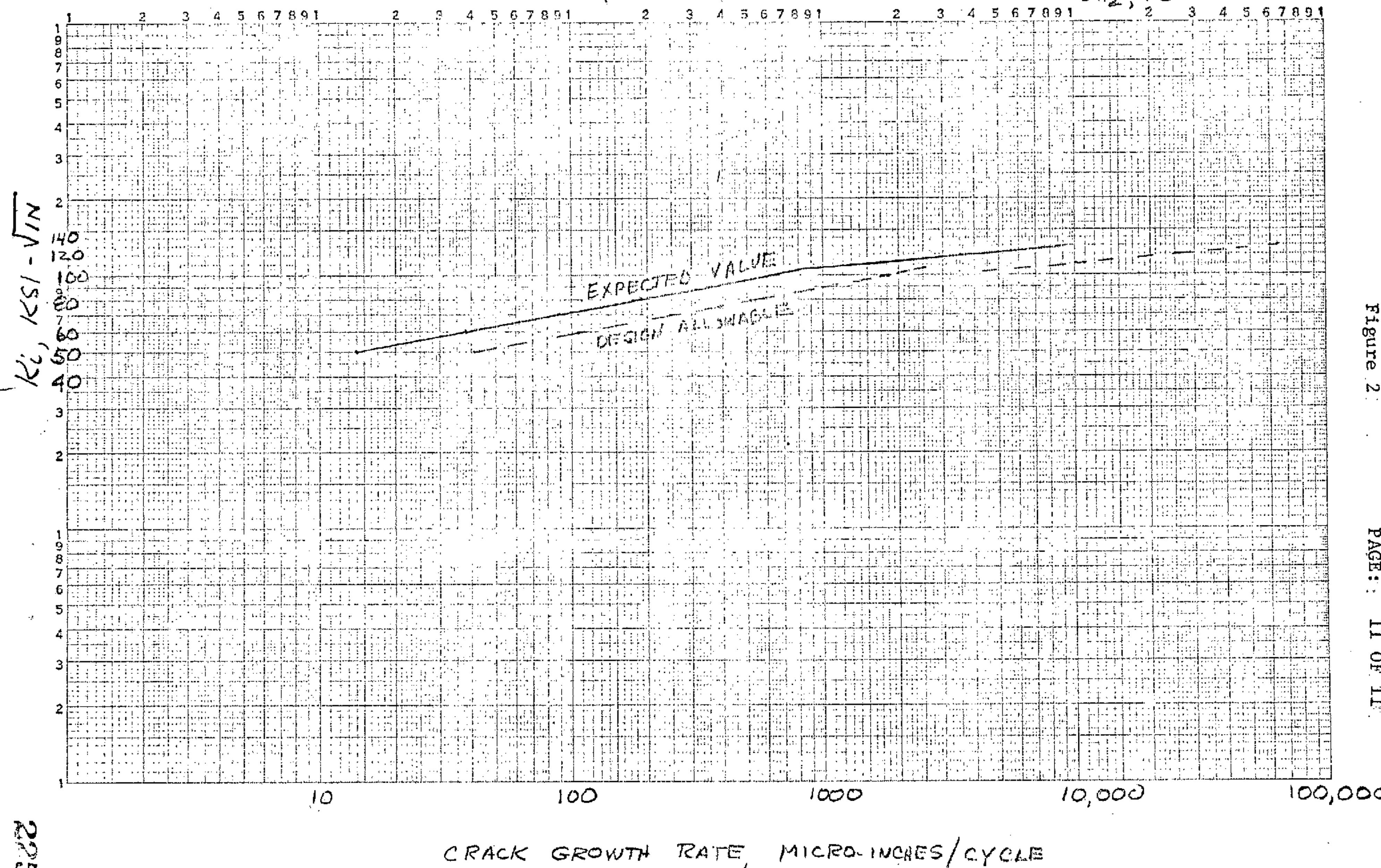

Figure 2

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